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Research article

A framework for the sustainable maintenance of permanent runoff management structures in rainfed agriculture under climate change

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ABSTRACT

Rainfed agriculture supports a significant share of global food production, balancing water storage with competing demands through runoff management. Human interventions to manage runoff range from temporary practices (e.g., tillage adjustments, crop residue retention) to permanent structures such as terraces and ditches. While practices are adaptable, structures are less flexible but critical for climate resilience. Their life-cycle comprises design/construction, maintenance, abandonment/destruction, and rehabilitation. Despite extensive research on design, rehabilitation, and abandonment, the description, understanding, and impact of maintenance practices remain understudied. This paper addresses this gap through a configurative review (1954–2024), integrating scattered knowledge. We show that rainfall variability, driven by climate change, accelerates biophysical degradation (e.g., terrace deformation, ditch occlusion), requiring adaptation and knowledge sharing to ensure structural stability and hydrological connectivity. Results highlight how regional inconsistencies in structure names hinder cross-regional comparisons and research consolidation. Our contributions include a framework for standardizing: (1) a context-specific evaluation of maintenance practices and (2) an assessment of runoff management structure efficiency under climate change. By integrating biophysical durability, socioeconomic feasibility, and adaptive governance, this framework provides stakeholders and academic actors with a common basis for systematically evaluating and improving runoff management. In practice, we urge policymakers and practitioners to adopt proactive, climate-adaptive maintenance, and to incentivize local community involvement for hybridizing traditional knowledge and technical innovation. By integrating maintenance into farming system design and management, these structures may effectively mitigate the impacts of an increasingly unpredictable climate, ensuring long-term resilience and sustainability in rainfed agriculture.

1. Introduction

Rainfed agriculture accounts for approximately 80% of global cropland and contributes over half of the world's food production (FAO, 2020). In these farming systems, effective runoff management is critical for balancing water storage for crop root zones, aquifers, and reservoirs, while accounting for competing demands for agricultural, industrial, and domestic water uses (Rockström et al., 2007). Runoff management also safeguards water quality and soil health by mitigating offsite impacts such as floods and related transports of sediments or pollutants (Adimassu et al., 2017). These functions are increasingly vital as climate change amplifies rainfall extremes, increasing disparities in water availability and crop needs (Konapala et al., 2020).

Runoff management ranges from local to landscape-level interventions encompassing temporary practices (e.g., tillage adjustments, crop residue retention) and permanent structures such as terraces and ditches (Woldearegay et al., 2018). While temporary practices can be adapted to seasonal shifts, permanent structures are less flexible but provide long-term resilience against intensifying droughts and deluges (Rajbanshi et al., 2023). Their extended lifespan, however, entails a complex life-cycle: (1) *design and construction* tailored to local conditions; (2) *maintenance* to counter degradation, improve service provision, or adapt to moderate changes in context; (3) *abandonment or destruction* due to any persistent lack of maintenance, possible design/-construction errors, as well as improper maintenance practices, or drastic changes in biophysical or sociotechnical context; and (4)

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rehabilitation informed by lessons learned from previous lifecycle stages (Tarolli et al., 2019).

Despite extensive research on design, abandonment, and rehabilitation, the description, understanding, and impact assessment of maintenance practices for permanent structures remain understudied (Sofia and Tarolli, 2017). Climate change exacerbates this gap: intensified rainfall accelerates the consequences of soil erosion (e.g., terrace deformation and collapse, ditch siltation and occlusion), demanding urgent maintenance of these structures in flood-prone regions (Zittis et al., 2022), while prolonged droughts reduce the perceived need for maintenance, leading to its neglect (Meaza et al., 2022). In addition, localized knowledge silos and ambiguous terminology hinder cross-regional learning and multi-stakeholder governance (Moreno-de-las-Heras et al., 2019).

This study aims to advance the understanding of maintenance practices for permanent runoff management structures in rainfed agriculture under climate change. To achieve this, we propose a novel framework that allows for a systematic description and understanding of maintenance practices, challenges, and adaptive strategies through a configurative review of interdisciplinary literature (1954–2024). Our objectives are threefold: (1) to synthesize biophysical and socioeconomic drivers of maintenance in diverse agropedoclimatic contexts, (2) to frame the efficiency assessment of permanent structures under intensifying hydroclimatic extremes, and (3) to translate these insights into a replicable decision-support framework for stakeholders. By bridging fragmented terminology and knowledge, this framework supports stakeholders and researchers in comparing context-specific maintenance, ensuring that runoff infrastructure remains resilient, cost-effective, and environmentally sustainable. Ultimately, this work seeks to shift the discourse on runoff management from reactive repairs to proactive, climate-adaptive stewardship.

The remainder of the paper details the configurative review methodology, including source selection and synthesis criteria (Section 2), illustrates key points from the state of the art (Section 3), highlights critical gaps in the research about maintenance practices (Section 4), and focuses on climate change impacts on runoff management structures and the evolving maintenance needs (Section 5). In conclusion, we identify policy and practical implications for embedding proactive maintenance into climate-resilient farming systems (Section 6).

2. Review approach

Onsite runoff management structures (i.e., those whose effects are targeted within their local area) result from actions aimed at increasing soil water content through controlled infiltration. Among land-shaping interventions, terraces and ditches (Fig. 1) represent two archetypal structures with distinct hydrological functions. Terraces are convex, stepped structures constructed using dry-stone masonry or earthen risers to reduce slope gradient, minimize erosion, and create cultivable platforms for agriculture (Tarolli et al., 2014). Ditches are concave, elongated structures organized in networks to channel excess runoff away from fields, preventing waterlogging and gully formation (Levavasseur et al., 2016). While terraces and ditches are among the most studied and globally prevalent structures, runoff management structures encompass a wide diversity of regionally specific earthworks (e.g., contour bunds, retention basins) or built structures (e.g., stone bunds) (Fig. 1). However, the lack of a standardized terminology or taxonomy hinders the systematic analysis of these structures. For example, the term "terrace" may refer to stone-walled platforms in Mediterranean contexts, but to earthen embankments in Southeast Asia. This terminological heterogeneity precludes an exhaustive review of all variants.

2.1. *Configurative mapping review*

The context-dependent and semantically ambiguous nature of runoff management structures necessitated a configurative mapping review. This method is ideal for understudied topics, as it synthesizes interdisciplinary evidence to identify patterns, relationships, and gaps (Gough et al., 2012). Comparatively, aggregative reviews synthesize homogeneous evidence from narrowly defined topics using exhaustive database searches. Three reasons motivated our choice for a configurative mapping review: (1) the terminological heterogeneity that impeded keyword-driven literature retrieval; (2) the interdisciplinary scope of maintenance practices required synthesizing insights across disciplines such as agronomy, hydrology, and socioeconomics, where methodologies and vocabularies diverge; and (3) the emergent conceptualization demanded inductive analysis, as limited prior theorization left drivers, barriers, and outcomes of maintenance inadequately mapped. By iteratively refining search terms and integrating gray literature (e.g., technical reports, policy documents), this method allowed us to balance breadth and depth, clarifying keyword taxonomies while preparing for future targeted reviews (Vanhala et al., 2022). The absence of comparable effect size measurements in the literature studied—due to the difficulty of identifying control cases—also prevented us from carrying out a meta-analysis.

2.2. *Sampling strategy*

The sampling strategy was guided by purposeful selection based on iterative adjustments until we reached a point of saturation, where new studies were no longer adding relevant insights. The sampling of the literature included three phases: search queries, identification of key documents, and expansion to the cited and citing references (Fig. 2).

2.2.1. *Phase 1: search query design and refinement*

Initial search queries tested in Web of Science, Scopus, and Google Scholar combined terms such as "runoff management," "green water," "terraces," and "maintenance" with agricultural contexts (Table 1). Queries were progressively refined to exclude urban runoff, rooftop

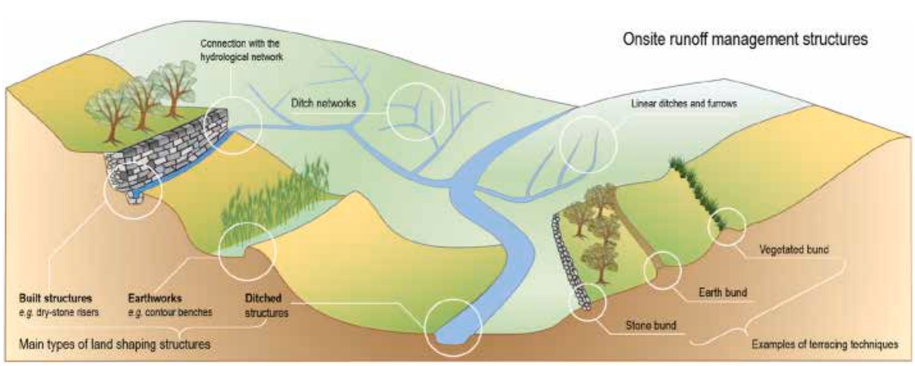

Fig. 1. Schematic illustration of the onsite runoff management structures. Adapted from Wang et al. (2022b).

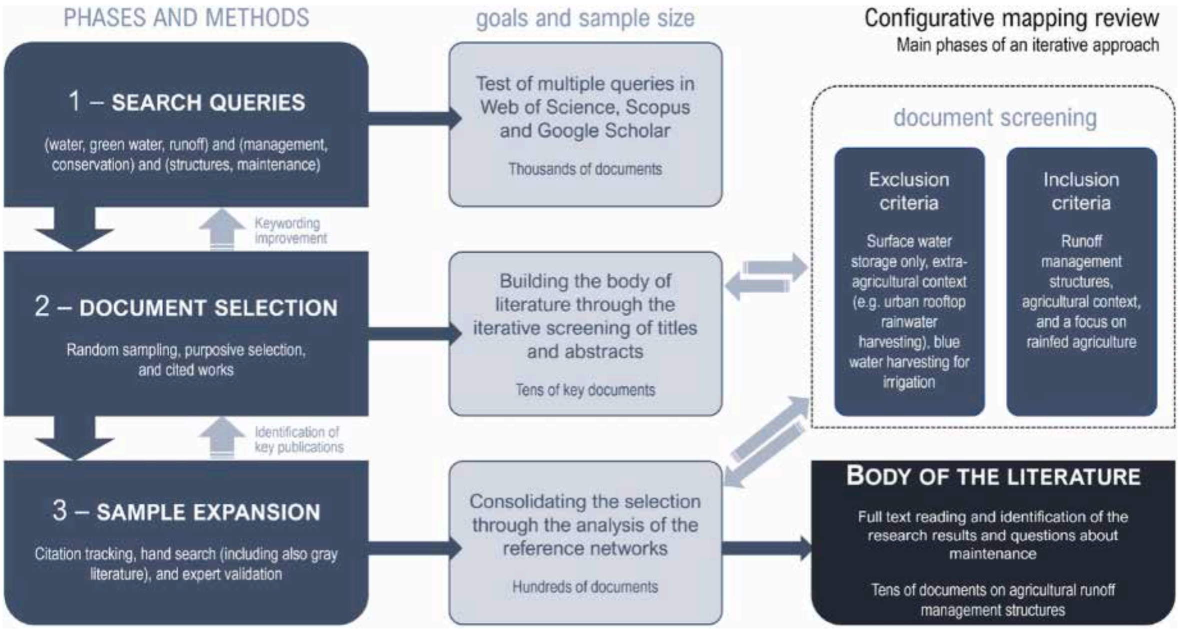

Fig. 2. Workflow of the configurative mapping review for literature sampling. Three iterative phases guide the process (left column): design and refinement of the search queries, document selection, and sample expansion. Each phase has specific goals eventually defining the sample size (central column). The document screening and selection were guided by inclusion/exclusion criteria (right), which were iteratively refined to achieve thematic saturation. Arrows denote workflow direction and feedback iterations.

water harvesting, and non-structural conservation practices (e.g., crop rotation). For example, proximity operators (e.g., W/3) helped narrow results to documents explicitly linking runoff structures to agricultural resilience (see Table 1 for full syntax). The results for Google Scholar are not reported, as they are not reproducible because it is a crawler-based web search engine and not a curated database like the other two.

2.2.2. Phase 2: document selection

To minimize selection bias, we first randomly sampled titles/abstracts from search results. Subsequently, purposeful sampling ensured the representation of diverse theoretical approaches (e.g., hydrological modeling, socioeconomic case studies), geographic contexts (e.g., Mediterranean terraces, Asian contour bunds), and document types (peer-reviewed articles, gray literature). High-impact studies (e.g., Tarolli et al., 2014) and landmark technical reports and books (e.g., Mekdaschi Studer and Liniger, 2013) were prioritized to anchor the review in established knowledge.

2.2.3. Phase 3: sample expansion

To ensure comprehensive coverage, we expanded the sample through three complementary strategies (Fig. 3): (1) backward citation tracking, where reference lists of key documents were hand-searched to identify foundational studies from the past two decades, further expanding to earlier landmark works omitted by database algorithms; (2) forward citation tracking, which traced newer publications citing key documents to capture emerging applications (e.g., machine learning for terrace erosion modeling); and (3) expert validation, involving consultations with agronomy and hydrology specialists to confirm the inclusion of regionally significant terminology (e.g., “fanya juu” terraces in East Africa) and overlooked gray literature.

2.2.4. Inclusion and exclusion criteria

Guided by iterative refinements, criteria were finalized as follows: (1) *Inclusion* required studies to explicitly address structural runoff management (e.g., terraces, ditches) within agricultural contexts, particularly those analyzing lifecycle phases (e.g., maintenance challenges, abandonment drivers) or agropedoclimatic factors (e.g., soil type, rainfall variability). (2) *Exclusion* eliminated documents focused on non-structural practices (e.g., cover cropping), irrigation infrastructure (e.g., canals, drip systems), or non-agricultural settings (e.g., urban storm water management). These criteria ensured thematic coherence while allowing for interdisciplinary coverage.

2.3. Document screening and analysis

To summarize the retrieved literature, we employed a pragmatic, descriptive synthesis approach, emphasizing qualitative analysis over quantitative methods due to the thematic and contextual diversity of the literature body. This process focused on identifying recurring patterns in maintenance challenges, interventions, and outcomes across a few hundred documents. The resulting synthesis informed a global case study panel, which underpins our analysis of current knowledge (Section 3) and critical gaps (Section 4) in the maintenance of onsite runoff management structures.

3. Current understanding of runoff management structures and maintenance

Onsite runoff management structures display considerable heterogeneity in design, nomenclature, and ecohydrological functions across agricultural regions. To facilitate cross-contextual analysis of maintenance practices, this study developed a classification framework (Fig. 4) based on three runoff management actions satisfying three ecohydrological functions: infiltration enhancement for soil retention (e.g., terraces), short-term runoff storage for water harvesting (e.g., contour benches), and runoff routing for water drainage (e.g., ditches). The framework allows the comparison of structures despite terminological inconsistencies, such as regional variations in structure naming. It also enables the identification of main degradation drivers, including erosion, sedimentation, and vegetation overgrowth. Finally, this framework sets the background to define and compare maintenance interventions, such as sediment removal, structural repairs, and vegetation management. This approach to maintenance definition distinguishes it from adjacent lifecycle phases (e.g., rehabilitation,

Table 1
Search strategy syntax and results across literature databases. Example searches queries tested in Scopus (sco-) and Web of Science (wos-), in titles, abstracts, and keywords, or topics (TS) respectively. Coding: sub = subject area filter (e.g., sub = agronomy), not = exclusion operator, & = AND operator, (…, …) = OR operator, W/n = proximity operator, with n indicating the number of words of distance. The complete search tests are available at the following address https://doi.org/10.5281/zenodo.14599688.

ID	Search	dd-mm-yy	Results	Notes
sco-s10	(soil, water) & manag* & (agri*, agro*)	02-06-23	80,293	Too large body
sco-s18	soil & water & manag* & (agri*, agro*, farm*)	02-06-23	25,737	Relevant results, but a too large body
sco-s61	soil & (water*, hydro*, runoff) & (manag*, conserv*, harvest*, storage, collect*, practice, system, infrastructure, technique*, method*, pattern*, config*) & mediterranean. sub:agri	02-06-23	2691	Inclusion of relevant terms, with a focus on the Mediterranean region. The semantic analysis in CorTexT showed that the main topics are soil and water conservation practices, and various regional levels, but no structures
sco-w10	((water, runoff) W/2 (harvest*, conserv*)) W/2 (agriculture*, farm*, practice), not (irrigate*, roof*, watermelon)	23-07-23	1646	Interesting results, but focus on water. Need to integrate soil conservation structures
sco-ro02	(runoff W/2 manage*) & (agric*, agro*, farm*, rural)	07-12-23	336	Relevant results, but body too limited
wos-gw-06	"green water"	01-08-23	1622	Search for documents about green water

abandonment), clarifying its role in preserving structure efficacy under dynamic climatic and agronomic conditions.

3.1. Framework proposal for comparing onsite runoff management structures

In rainfed farming systems, runoff management strategies historically prioritize three actions (Fig. 4): (1) enhancing soil infiltration for subsequent storage in the crop root zone and the underlying shallow aquifer, (2) storing runoff in surface, short-term, human-made reservoirs, and (3) routing excess water via engineered pathways (e.g., ditches) (Mekdaschi Studer and Liniger, 2013; Rockström and Falkenmark, 2015). These strategies, refined over centuries to align with local agropedoclimatic conditions (Tarolli et al., 2014), serve multiple eco-hydrological functions: (1) increasing infiltration (run-on) and thus water storage in the crop root zone and in the underlying shallow aquifer, (2) increasing local water availability in small surface ponds for various uses or aquifer recharge, (3) reducing downstream flooding, and (4) reducing soil erosion and subsequent siltation of downstream anthropic surface structures or natural water bodies. Beyond these primary purposes, these structures also contribute to agricultural productivity and provide additional ecosystem services by influencing nutrient cycling and biodiversity conservation (Boivin and Crowther, 2021; Rudi et al., 2022; Vohland and Barry, 2009; Ward-Campbell et al., 2017). These contributions relate to modification in soil fertility status along to soil gradients (Taye et al., 2013), the potential increases in biomass production (Kugedera et al., 2022), and the role of seed banks and corridors for the dispersal of natural vegetation (Faucher et al., 2024; Louhaichi et al., 2022). Notably, their ecological contributions—including legacy effects on hydrology and vegetation post-abandonment—persist even after structures fall into abandonment (Nichols et al., 2023).

All these individual structures relate to the local level, although they need to be organized into a broader system to connect with the hydrological network and the farming system (Bellin et al., 2009; Levavasseur et al., 2016). Thus, runoff management structures can be addressed at two different levels: the individual structure and the system. Farmers' maintenance priorities often reflect trade-offs between localized benefits and system-wide resource allocation (Rudi et al., 2022; Tarolli et al., 2019).

Existing literature reviews have addressed runoff management structures mainly on the basis of technical considerations: local morphology, construction materials, and structural engineering complexity (Mekdaschi Studer and Liniger, 2013; Woldearegay et al., 2018). Some comparative and participatory studies have also highlighted the role of soil variability and farmers' perceptions in optimizing placement on sloping areas (Bizoza and de Graaff, 2012; Piemontese et al., 2020). Meta-analyses disproportionately focus on terraced systems (Arnáez et al., 2015; Tarolli et al., 2014; Wei et al., 2016), particularly in Mediterranean regions (Moreno-de-las-Heras et al., 2019; Stanchi et al., 2012). Conversely, reviews on water harvesting are less frequent and relatively old (Biazin et al., 2012) or geographically limited (Rizzo et al., 2022; e.g., Ziyadi, 2011). Overall, the World Overview of Conservation Approaches and Technologies (WOCAT) database, though reliant on voluntary submissions, remains the most comprehensive global repository including data on runoff management structures (Liniger and Critchley, 2008).

3.2. Heterogeneity in naming runoff management structures

What emerges from the available literature is the great heterogeneity in naming runoff management structures, essentially reflecting regional adaptations to agropedoclimatic conditions, knowledge systems, and hydrological priorities (Fig. 5). The wide range of names arises from distinct local approaches to soil and water management, water harvesting (Beckers et al., 2013), and soil or land conservation (Chen et al.,

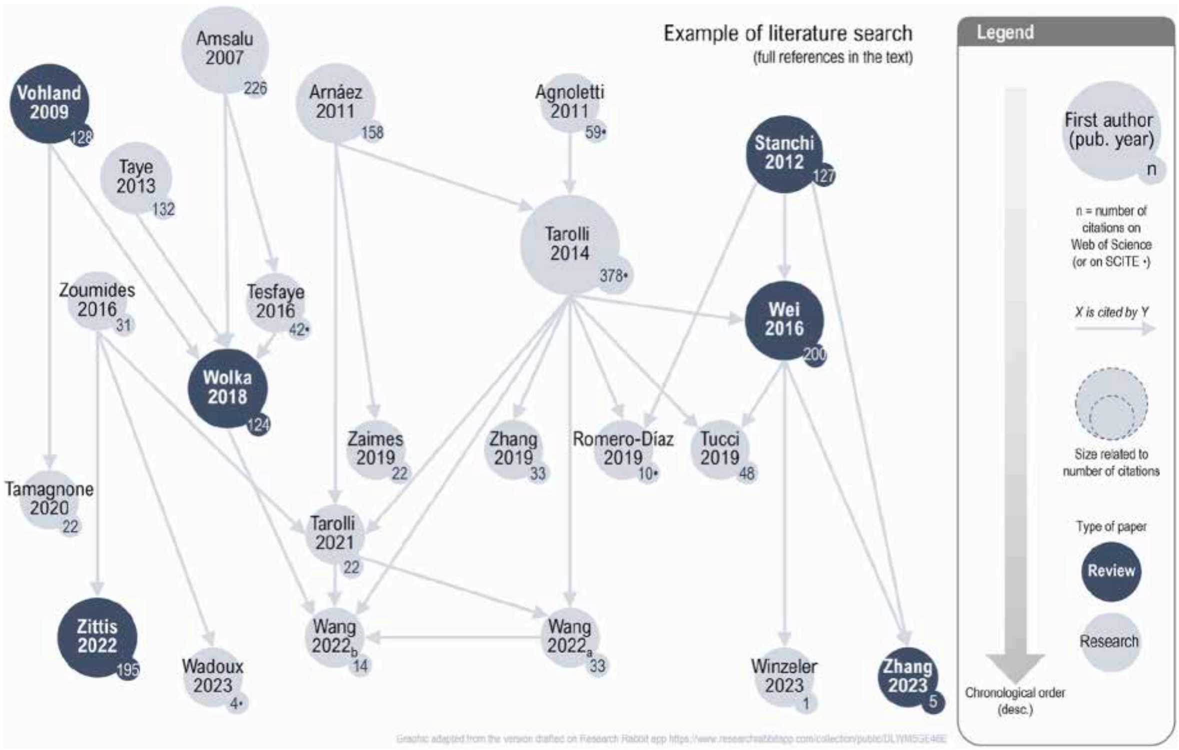

Fig. 3. Sampling strategy for literature expansion. Key documents were contextualized through: (1) backward citation tracking (reference lists of selected papers), (2) forward citation tracking (papers citing key works), and (3) expert validation to identify landmark studies and emerging applications. Screening prioritized relevance to agricultural runoff structures, citation impact, and methodological diversity.

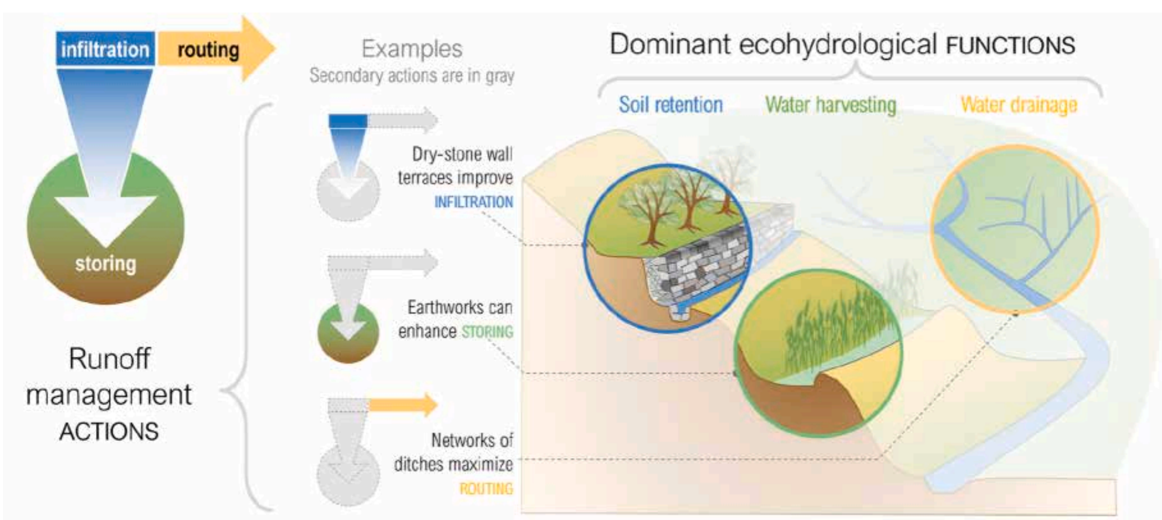

Fig. 4. Framework for comparing onsite runoff management structures by runoff management actions (left) and dominant ecohydrological function (right). Adapted from Mekdaschi Studer and Liniger (2013), and Rizzo et al. (2024).

2017; Dorren and Rey, 2004). Brown et al. (2020) illustrated this ambiguity in their analysis of terraces and lynchets, where subtle morphological differences (e.g., riser height, slope gradient) yield overlapping classifications. In an attempt to capture the local variations in runoff management structures in rangelands, Stavi et al. (2020) distinguished high, medium, or low footprints according to the ecohydrological and geo-ecological magnitude of modifications required to establish the structures.

Regional names further distinguish functionally similar structures (Ambroise et al., 1993; Blanc, 2001; Critchley et al., 1994; Ziyadi, 2011). For example, equivalent structures can be named differently depending on the region, as in the case of "tabias" and "jessours" (Fig. 5-J) in southern Tunisia (Bonvallot, 1986; Nasri et al., 2004), or "tancats", "rascasses", and "cadennes" in southern France (Martin, 2006). While both are earth or stone structures designed to minimize soil erosion by reducing runoff speed, their different names reflect differences in runoff interception (distributed vs. concentrated flows) and construction traditions (Critchley and Siegert, 1991). Vernacular distinctions can also align with seasonal functionality: in Zambia's Barotse floodplain, farmers use separate terms for structures managing wet-season floods versus dry-season water retention (Del Río, 2014).

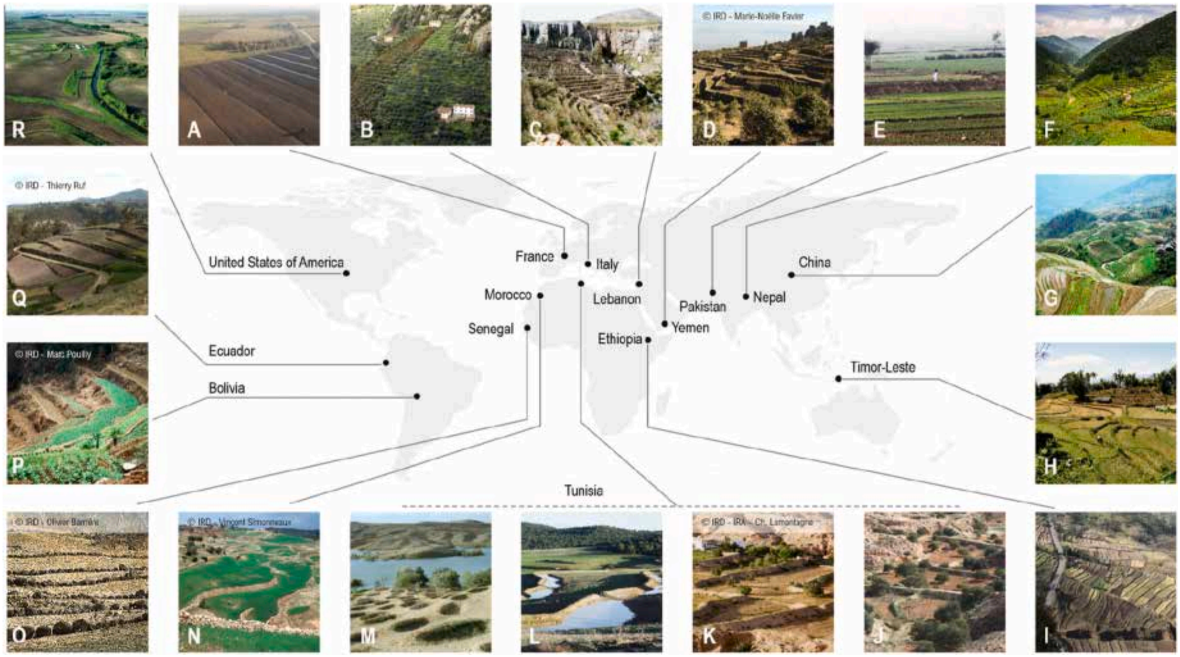

Fig. 5. Examples of the heterogeneity of shapes, materials, and naming of the onsite runoff management structures worldwide. Terrace naming is based on Chen et al. (2017) and Dorren and Rey (2004) unless otherwise specified by the authors of the photos. A - Dense network of drainage ditches, in the plain of Le Fay-Saint-Quentin, Hauts-de-France region (photo: Davide Rizzo, 2021). B - Olive grove monoculture on narrow bench terraces with dry-stone wall risers, Monte Pisano, Tuscany (photo: Davide Rizzo, 2007). C - Bench terraces at the Naba Laban falls, near Faraya (photo: Jean Albergel). D - Level terraces in Djebel Haraz (photo: IRD/Marie-Noëlle Favier, 2005). E - Recently sown paddy fields in Sindh (photo: DFID/Russell Watkins, 2010). F - Terraced paddy fields (photo: Sharada Prasad CS, CC BY 2.0, 2013). G - Terraced paddy fields, Longsheng (photo: Drolexandre, CC BY 3.0, 2008). H - "tiered rice paddies", south of Bacau (Kaiser et al., 2011 photo 2B). I - Slope terraces in north Wollo, Amhara region (photo: kindly provided by Sabine Planel and used here with her permission, 2010). J - "Jessour", a terraced wadi system for water harvesting (photo: Jean Albergel). K - Level terraces on loess soil, Ksar Hallouf, Mednine (photo: Christian Lamontagne, 2017). L - "Banquettes" also named contour benches (photo: Jean Albergel, 1999). M - Half-moon or crescent-shaped terraces (photo: Jean Albergel). N - Small dry-stone wall terraces at Iferhane, Rheraya Valley, western Haut-Atlas (photo: Vincent Simonneaux, 2004). O - "Anti-erosion protections" on a hillside field (photo: Olivier Barrière, 2000). P - Zig terraces (photo: Martin et al., 2010). Q - Slope terraces in Santa Rosa region (photo: Thierry Ruf, 2004). R - Stream buffers (photo: Lynn Betts, U.S. Department of Agriculture, 2010).

3.3. Boundaries for the concept of maintenance and examples

Maintenance in agricultural contexts encompasses practices: (1) to repair and/or adjust a system in order to ensure its continued functioning, or (2) to maintain optimal efficiency and reliability in a production process (FAO, 2023). While traditionally associated with machinery and equipment, maintenance and its timeliness can impact the overall farm performance, requiring alignment with farming calendars, the specific geographical context, and accurate scheduling and forward planning. Although a comprehensive and systematic description of the maintenance of runoff management structures is beyond the scope of this paper, we present hereafter the main types of practices based on the sources of natural obsolescence and degradation (Fig. 6).

Runoff management structures require maintenance due to hydroclimatic events (Brandolini et al., 2018a), soil erosion (García-Ruiz and Lana-Renault, 2011), landslides (Brandolini et al., 2018b), vegetation overgrowth (Cammeraat et al., 2005; Rudi et al., 2022), machinery misuse (Pijl et al., 2019), wildlife damages (Mauri et al., 2019), trade-offs stemming from changes in land tenure and livestock (Amsalu and de Graaff, 2007), and abandonment (Lesschen et al., 2008). All of these were also illustrated in the Italian manifesto for terraced landscapes, presented at the 3rd World Meeting of the International Terraced Landscape Alliance, to frame the alternative futures for these structures (ITLA et al., 2019). These factors drive three primary physical degradation processes: deformation, loss of structural integrity, and occlusion. For example, in the case of terraces, the occlusion of the internal drainage of the raisers, when made of dry-stone walls, can lead to their progressive deformation (i.e., bulging) up to their collapse (Carl and Richter, 1989; Rizzo et al., 2022), which is eventually replicated along concentrated flow paths across any hydrographical network (Brandolini et al., 2018a; Cambi et al., 2021; Crosta et al., 2003; Preti et al., 2018b). In the case of ditches, the occlusion induced by soil erosion and vegetation overgrowth directly alters the flow section (Rudi et al., 2022).

The description of maintenance can also refer to the energy required to compensate for the physical processes that cause degradation (Fig. 6). For example, structures that involve soil shaping and ditching will require energy that is either provided by animals or machines, or is limited to human manual labor (Nyamadzawo et al., 2013). Constructed structures such as dry-stone terraces or stone bunds also require the provision of materials and the availability of skilled labor (Zougmoré et al., 2014). Their diversity can also be leveraged to explain or predict patterns of abandonment (Solé-Benet et al., 2010). For example, a high density of terraces or earth dams can become a nuisance for farmers and land managers if they impede machinery access (Bellin et al., 2009; Ramos et al., 2007). In summary, the greater the temporal frequency and spatial extent of the energy to be applied to compensate for degradation, the greater the intensity of, and dependence on, maintenance (Tarolli et al., 2019).

Maintenance needs are subjectively assessed, as the effectiveness of agricultural runoff management structures is still not well defined (Kizos et al., 2010), while only a few studies have addressed the effectiveness of maintenance practices on structures (Critchley and Mutunga, 2003; Dangiso and Wolka, 2023; Smit et al., 2017; Srivastava et al., 2023). The limited literature available on maintenance shows contrasting results regarding the effects of insufficient maintenance, mainly in relation to the age of abandonment. In the case of terraced systems, Moreno-de-las-Heras et al. (2019) noted that the development of vegetation, especially forest cover, following long periods of abandonment can

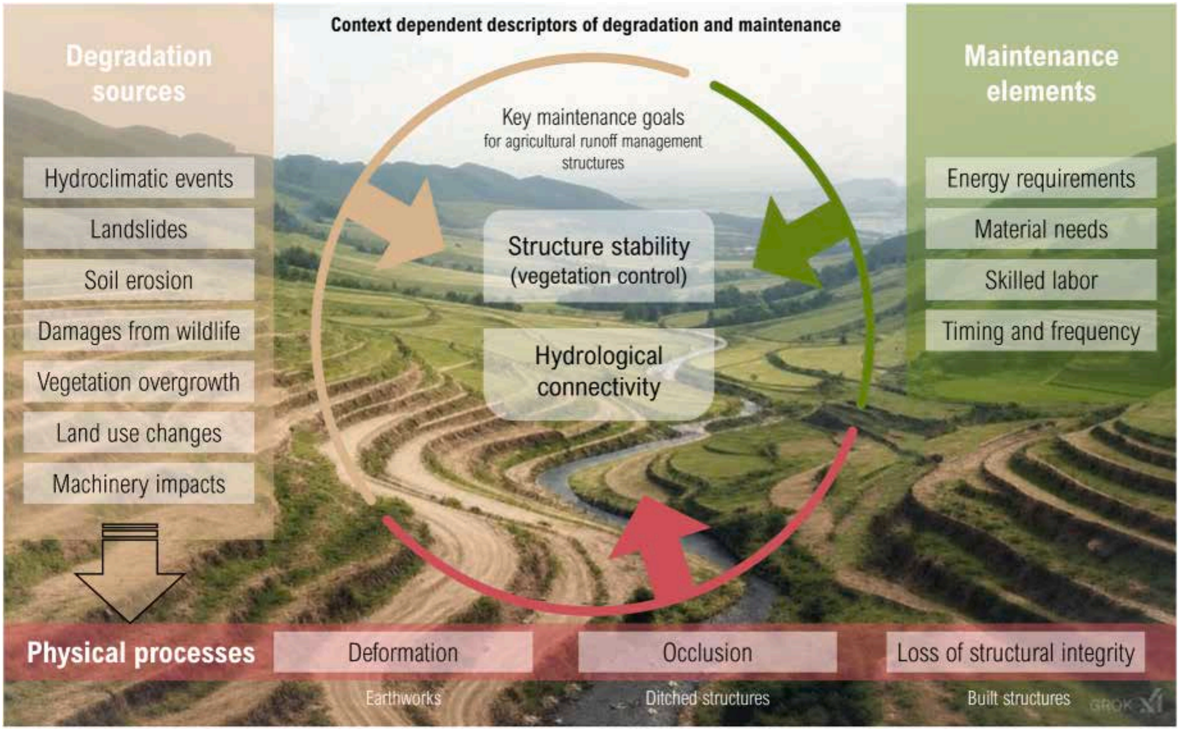

Fig. 6. Conceptual summary of drivers and processes of degradation in runoff management structures. Key degradation sources (left) and physical processes (center) necessitate maintenance interventions (right), with energy inputs (labor, materials) scaling with degradation severity. Background image: Conceptual representation of structures (GrokAI-generated).

reduce the hydrological connectivity of individual terraces within a terraced landscape, thus "attenuating the negative effects of terrace collapse on catchment-scale flow arrangement and flooding". Similarly, Cevasco et al. (2014) observed a lower landslide risk for long-abandoned terraces compared to more recently abandoned terraces. Landslides triggered by extreme rainfall events were less frequent on long-abandoned terraces (>15 years) with dense vegetation cover than on recently abandoned terraces and cultivated terraces, while maintenance proved crucial for the actual stability of the latter (Brandolini et al., 2018a; Cevasco et al., 2013; Pepe et al., 2019).

Overall, the contribution of vegetation cover to the stability of terraces after abandonment is debated: the denser and older the vegetation, the greater the infiltrability in the upper soil layer, although deep root anchoring (>40 cm) can be limited by the anthropic origin of these structures and induce potential subsurface slip planes (Cammeraat et al., 2005; Carl and Richter, 1989). In addition to natural degradation and abandonment, improper maintenance can also be problematic (Wei et al., 2016). In summary, these results highlight—at least for

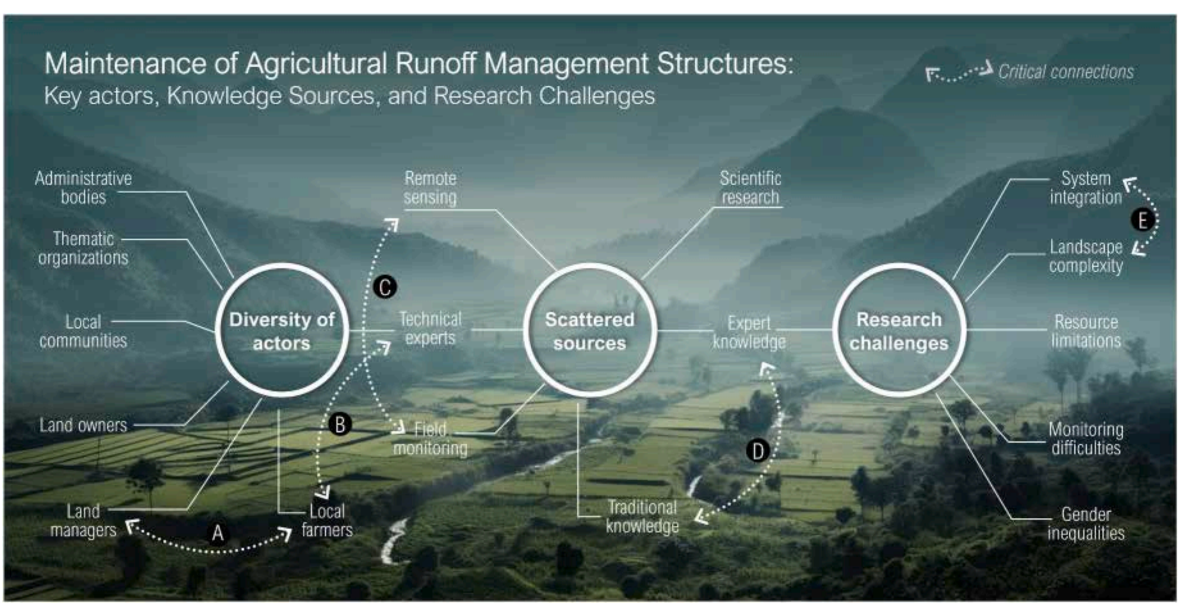

Fig. 7. Conceptual summary of the three research topics to be addressed regarding maintenance of agricultural runoff management structures. The letters highlight critical connections between: the farmers and other local managers (A) or the technical experts (B); field monitoring and remote sensing (C); traditional and expert knowledge (D); and the landscape complexity of the structures with the system integration of their maintenance (E). Background image from lummi.ai.

terraces—the need to describe and understand the maintenance, as it is crucial to ensure terrace stability both for cultivated areas (Rizzo et al., 2022) and for vegetation cover after abandonment (Arnáez et al., 2011).

4. Critical topics to be addressed about maintenance of runoff management structures

Building on the gaps identified in Section 3, this section synthesizes three priority topics to advance research about the maintenance of runoff management structures (Fig. 7). First, the study of the maintenance practices that raises specific challenges due to the scattered knowledge across multiple actors and the difficulties in monitoring (Table 2). Then, the integration of traditional structures and knowledge with innovations that can provide relevant technical alternatives for maintenance and rehabilitation. Finally, the inclusion of maintenance practices in the broader research about farming system management.

4.1. How to collect and integrate scattered knowledge and field evidence

Designing and constructing permanent runoff management structures requires diverse expertise, from routine farming practices to specialized hydraulic engineering. While scientific literature often emphasizes theoretical hydrological modeling or post-construction assessments (e.g., erosion, flood risks; Camera et al., 2018; Prosdocimi et al., 2015), expert knowledge remains largely theoretical and focused on initial construction phases (ASABE, 2021; Hussein et al., 2016; Yeomans, 1958). This gap highlights the need to integrate practical, field-based insights from local stakeholders and farmers, as well as other knowledge and data sources (Table 2).

4.1.1. Integrating local and expert knowledge

Farmers and land managers hold relevant context-specific knowledge for maintaining locally designed runoff management structures (Fig. 7A and B). Their practices mediate biophysical processes, leading either to land degradation (Smit et al., 2017) or to sustainable land management (Sanz et al., 2017; Wang et al., 2022b), and adapt to evolving pressures such as climate change (Aguilera et al., 2020), societal expectations for agricultural intensification (Pretty et al., 2018), or sustainability issues (Zhang et al., 2023). Traditional structures, refined over centuries (Levavasseur et al., 2016; Ndlovu et al., 2020; Nyagumbo et al., 2019), highlight the value of ethnographical and archaeological insights in preserving environmental heritage (Bevan et al., 2013; Brown et al., 2020; Gashure and Wana, 2023). For instance, even simple stone bund terraces influence soil heterogeneity, prompting farmer adaptations (Wolka et al., 2018).

4.1.2. Community engagement and equity

Environmental organizations advocate for maintenance training and community coordination, often involving women, whose grassroots leadership improves effectiveness despite facing barriers in technical roles (Ndeke et al., 2021). Gender-sensitive strategies that address resource access, labor division, and decision-making can improve both equity and effectiveness. In general, maintenance should ideally be integrated from the design stage, involving as much as possible the concerned farmers and local actors in charge of the structures (Abi et al., 2018; Critchley et al., 1994). This includes identifying the principles and techniques to be taught to farmers and other actors involved in maintenance (Cicinelli et al., 2021; Kremenić et al., 2021). Residents and community members also play an important role by participating in community maintenance efforts, monitoring and reporting, and following best practices (Gennai-Schott et al., 2020).

4.1.3. Data sources integration and monitoring challenges

Complex, multi-level observatories face challenges in integrating the monitoring of maintenance practices due to their dependence on socio-technical processes that are difficult to replicate experimentally, particularly over the extended lifespans (>15 years) of permanent structures (Rajbanshi et al., 2023). However, integrating biophysical and socio-technical knowledge at different spatial and temporal levels could help to clarify the roles of various actors within the system. Remote sensing offers scalable tools to address these gaps: satellite and airborne data enable system-level assessments of terrace geometries (Cazorzi et al., 2013; Rizzo et al., 2007), damage detection (Cucchiaro et al., 2021; Tarolli et al., 2021), and hydrological connectivity (Dai et al., 2020; Spanò et al., 2018; Tucci et al., 2019; Winzeler et al., 2023). These methods are indispensable for mapping hazardous or abandoned

Table 2
Sources for characterizing maintenance actions and costs for runoff management structures, considering strengths, weaknesses, and the ability to address variabilities of structures and maintenance across different contexts or climatic conditions.

Type of source	Description	Strengths	Weaknesses	Variability addressed	References (examples)
Data from existing projects)	Curated collection of field data from case studies	Provides empirical evidence, potentially large datasets	Heterogeneous data quality and comparability without a generally accepted framework	Can enable comparison across contexts and climates if referred to harmonized definitions	Use of WOCAT, as in Romero-Díaz et al. (2019)
Farmers and stakeholder assessments	Capture local knowledge and perspectives	Accounts for subjective drivers and perceived costs	Subjective and biased without a general framework. May not reflect actual cost accurately	Can provide insights into perceived variability based on local knowledge	WOCAT questionnaires, as described by Critchley and Mutunga (2003)
Cost-benefit analyses	Formal comparison of costs and benefits of maintenance	Comprehensive economic evaluation	Data-intensive approach that requires the collection and harmonization of comparable data	Differences in the sociotechnical systems can determine the variability of the cost-benefit balance	Giger et al. (2018)
Modeling approaches	Allows for predictions and scenario analysis	Can account for a variety of factors and their interactions	Model accuracy depends on data quality and model validity domain	Can incorporate variability drivers (e.g., rainfall, soil type)	Use of PESERA-DESMICE by Fleskens et al. (2016)
General guidelines	Simplified estimations, for instance, using rapid appraisal methods	Offer a starting point for cost estimation where other data are lacking	Lack of accuracy with incertitude level difficult to quantify	Depending on the definition of the guidelines, can be limited	Cramb et al. (1999) about the adoption of soil conservation measures
Literature reviews	Summary of existing knowledge	Structured comparison to identify available data	Require a clear framework to enable the comparison of heterogeneous sources (e.g., scientific and gray literature)	Can identify key drivers influencing structures across different studies	Tepes et al. (2021)
Field assessments	Direct observation or experimentation, also in association with land user interviews	Provide site-specific and updated information to complete and ground remote sensing data collection	Time-consuming and labor-intensive	Baseline reference for documenting and comparing different sites and conditions	Rizzo et al. (2022)

terrains or reforested agricultural areas (Cucchiaro et al., 2020; Fang et al., 2023), or for compiling regional inventories (Lu et al., 2023; Tecilla and Cosner, 2024). However, field assessments remain critical for validating remote observations at the level of individual structures (Pijl et al., 2021), comparing actual versus estimated ditch flows (Avilés et al., 2018), or tracking embankment erosion in drainage networks (Prosdocimi et al., 2015) (Fig. 7 C). Emerging projects now integrate permanent sensor networks to monitor micro-scale weather and hydrological dynamics, enhancing failure prediction under climate extremes (Fiorucci et al., 2023; Vigo et al., 2020). These advancements refine strategies for mitigating instability risks (Preti et al., 2018b) and stress the need to enhance the integration between scattered data sources (Table 2).

4.2. Integrating technical innovation and traditional knowledge

Integrating technical innovation with traditional knowledge presents opportunities to enhance runoff management across three levels: individual structures, system-level spatial arrangements, and community-level collaboration. At the level of individual structures, novel techniques such as bioengineering and nature-based solutions (Koutsovili et al., 2023; Nadal-Romero et al., 2022; Zaimes et al., 2019) can mitigate degradation while respecting ecological constraints and limited costs, though their effectiveness relies on maintenance, particularly when using living materials (Pepe et al., 2020) and needs to be compared with the local vegetation and the collectively perceived landscape identity (Gonzalez-Ollauri et al., 2023). The WOCAT database, despite geographic gaps due to its reliance on voluntary contributions, serves as a key repository for field-tested innovations like reinforced spillways and drought-resistant vegetation.

At the system level, reconfiguring the spatial arrangements of structures—such as integrating terraces with retention basins—can enhance runoff control under climate extremes, reducing sedimentation and flood risks (Tamagnone et al., 2020). At the community level, collaborative management models, such as shared maintenance of ditch networks or terraced systems, optimize resource use and labor equity (Cicinelli et al., 2021; Gennai-Schott et al., 2020; Koutsovili et al., 2023; Zoumides et al., 2016).

Successful integration relies on co-design with local communities to align innovations with cultural values and traditional practices (Fig. 7D). For example, Ethiopian farmers rejected expert-designed terraces that conflicted with indigenous soil classification systems (Dangiso and Wolka, 2023). Despite growing recognition of such synergies between local and academic knowledge in evaluating soil management (Guzman et al., 2018), few studies have evaluated knowledge hybridization for sustainable land management (Bouma, 2022; Martin et al., 2010) or the long-term effects of co-designing land management strategies (Critchley et al., 1994; Nyamadzawo et al., 2013; Wadoux and McBratney, 2023).

Cultural landscapes, recognized as world heritage sites by the United Nations Educational, Scientific and Cultural Organization (UNESCO), such as the rice terraces of the Philippine Cordilleras (Paing et al., 2022), or the agave landscape and ancient industrial facilities of Tequila in Mexico (Gullino and Larcher, 2013), exemplify systems that balance heritage preservation with adaptive innovation. This is also evident in other sites that highlight how traditional practices—refined over centuries—can inform modern engineering while sustaining ecological and cultural integrity (Bebermeier et al., 2023; Brown et al., 2020; Kladnik et al., 2017; Kremenić et al., 2021; Sabir, 2021).

4.3. Including maintenance practices in farming system management and research

Due to their long-lasting nature, runoff management structures embed rich traditional ecological knowledge (Boivin and Crowther, 2021), recognized globally by institutions such as the United Nations (Brown et al., 2020; Wang et al., 2022a). From this perspective, understanding their maintenance can inform and improve the strategies that local communities have developed in the face of long-term drivers such as climate change (Acovitsióti-Hameau, 2019). However, long-term (>15 years) studies of these structures remain scarce, leading to undervalued farmer contributions and underestimated efficacy compared to short-term conservation practices (Fenta et al., 2024; Rajbanshi et al., 2023).

These structures exemplify Anthropocene interdependencies between human and natural systems, where diverse actors—with varying skills and knowledge—shape the design, maintenance, and resilience of soil and water management (Boivin and Crowther, 2021; Guo et al., 2021; Tarolli et al., 2014). Understanding these dynamics requires acknowledging the non-linear environmental responses to human actions, and balancing the risks of unintended consequences with sustainable opportunities (Reyers et al., 2022). As Kemerink-Seyoum et al. (2019, p. 3) emphasize, documenting actual practices "creates room for acknowledging the messiness, creativity and contingencies", while also allowing for a better understanding of how "decisions and actions may be as much the outcome of pragmatic or tactical choices, as of strategic, power-laden ones". This perspective is particularly relevant given the renewed interest in pragmatism and ethnomethodology in sociotechnical studies, and the focus on practices as the observable component that links decision-making processes to the everyday materiality of local actions (Miettinen et al., 2009; Smit et al., 2017). In agriculture, focusing on maintenance practices clarifies barriers and incentives shaping farmer commitment to land management (Vuillot et al., 2016).

Economic studies have examined cost-benefit challenges in sustainable land management (Bizoza and de Graaff, 2012; Tesfaye et al., 2016) and the viability of implementing runoff management structures as part of sustainable land management projects (Giger et al., 2018). Nonetheless, system-level priorities may necessitate strategic "no maintenance" to optimize resource allocation (Rizzo et al., 2022; Tarolli et al., 2019). Effective maintenance relies on collaboration among key actors: property owners conducting routine upkeep, contractors handling complex repairs, and local governments providing oversight and support (Smit et al., 2017). This sociotechnical interdependencies (Fig. 7E), highlight the need for adaptive governance that aligns ecohydrological integrity with cultural and economic goals (Agnoletti et al., 2011).

5. Climate change and maintenance of runoff management structures

Climate change intensifies challenges for maintaining onsite runoff management structures in rural landscapes. Rising weather variability—including frequent droughts, heavy rainfall, and floods—accelerates structural degradation while complicating ecohydrological functionality. In flood-prone regions, degraded or improperly maintained structures require urgent maintenance to manage heightened runoff volumes (Qiu et al., 2023; Wang et al., 2022a; Zittis et al., 2022). Conversely, prolonged droughts diminish farmers' awareness of these structures' ecohydrological roles, leading to neglected maintenance (Meaza et al., 2022; Moreno-de-las-Heras et al., 2019; Wei et al., 2016). These dynamics exacerbate existing knowledge gaps in maintenance practices, particularly as extreme events amplify in magnitude and frequency. Compounding the issue, multi-actor management often results in conflicting priorities, with diverging perceptions of costs and benefits undermining coordinated responses. For example, terrace systems may face destabilization from intense rainfall even as drought-driven crop failures reduce incentives for communal maintenance, creating a cycle of disrepair (Tarolli et al., 2019).

5.1. Main consequences of climate change on degradation processes

Climate change directly alters rainfall regimes, the primary variable governing the design of agricultural runoff management structures.

According to the IPCC (2023, p. 48), intensifying droughts and extreme rainfall will disproportionately affect regions such as the Mediterranean. These shifts strain structures designed for historical climate norms, creating conflicting demands: intense rainfall necessitates enhanced water storage to mitigate flooding and erosion (Kizito et al., 2022), while prolonged droughts require maximizing infiltration to sustain green water availability for plants (Nasri et al., 2004). However, most structures prioritize one function over the other, leaving systems vulnerable to compounding stressors (Tamagnone et al., 2020).

5.1.1. Regional vulnerabilities and structural impacts

Nonetheless, Wang et al. (2022a) highlighted that steep-slope agricultural regions, where runoff structures are most prevalent, coincide with climate change hotspots. For example, Mediterranean terraced landscapes—covering vast areas (Stanchi et al., 2012)—face accelerated degradation under intense rainfall conditions, with wall collapses and wall piping (Pijl et al., 2021), or even terrace-cascading collapses and landslides (Moreno-de-las-Heras et al., 2019), following mechanisms that are specific to the physical characteristics of dry-stone walls (Camera et al., 2014; Carl and Richter, 1989; Preti et al., 2018a). Sediment loads issued from intense rainfall also affect the siltation of ditch networks, reducing their water conveyance capacity and increasing clearing frequency (Dollinger et al., 2017). Similar degradation mechanisms likely apply to structures such as *jessour* (Tunisian water-harvesting systems), contour benches, keylines, or trenches, though empirical evidence remains sparse (Mor-Mussery et al., 2023).

Droughts further destabilize structures by altering soil properties. Prolonged aridity increases soil friability, heightening erosion risks during subsequent rains—a critical issue for earthen structures like bench terraces. Droughts also affect agroecosystems in general through low resource use efficiency, particularly of nutrients and water (Wittwer et al., 2023), and disrupt edaphic communities, decreasing litter decomposition through reduced earthworm functional diversity (da Silva et al., 2020) or changes in the biomass, composition, and functions of edaphic microbial communities (Bérard et al., 2011). These effects may be magnified in runoff structures due to microclimatic extremes, though research is lacking.

5.1.2. Emerging complexities and knowledge gaps

Drier conditions may reduce vegetation overgrowth, thereby reducing maintenance requirements, but drought-flood cycles may trigger novel degradation pathways. For example, drought-weakened terraces may fail catastrophically under sudden hydraulic loading, while sediment occlusion from erratic rainfall exacerbates drainage inefficiencies. Such interactions remain poorly documented, despite evidence from Morocco, where droughts threaten terraced agroforestry through biodiversity loss (Ziyadi et al., 2019).

It is still difficult to assess the global spatial distribution of onsite runoff management structures. Gonzalez-Roglich et al. (2019) and Haregeweyn et al. (2023) presented a map of all sustainable land management practices worldwide and showed a close correspondence with aridity levels, although they included both agricultural runoff management structures as well as agronomic, vegetative and management measures. Prioritizing research on high-density regions (e.g., Mediterranean headwater ditches, Asian terraces) is critical to developing adaptive maintenance frameworks.

5.2. Maintenance needs to address climate-exacerbated degradation

In rainfed farming systems, climate change could exacerbate uncertainties in water availability, necessitating robust maintenance of permanent runoff structures to safeguard soil moisture for crops and mitigate erosion. Nature-based solutions like terracing, contouring, and pitting are increasingly advocated to enhance green water retention and climate resilience. However, the role of maintenance in preserving these structures under accelerating climate pressures still presents critical gaps and challenges.

5.2.1. Gaps in maintenance research

Current literature offers limited insights into maintaining hydrological functions under climate change. For example, studies on ditch maintenance focus largely on present-day conditions (Dollinger et al., 2017; Rudi et al., 2022), addressing biodiversity impacts (Faucher et al., 2024; Ward-Campbell et al., 2017), while others have focused instead on roadside ditches (Fernández-Raga et al., 2021; Kalantari and Folkeson, 2013; Schneider et al., 2019), yet with scarce attention to future climate scenarios. With regard to water infiltration to counteract drought, few studies have been devoted to the maintenance of drainage ditches (Avilés et al., 2018; Joel et al., 2015; Kocięcka et al., 2019), ditch networks for peatland drainage (Miettinen et al., 2020), or terraced slopes (Stanchi et al., 2012). In this context, Bellin et al. (2009) demonstrated that abandoned terraces lose 90% of their runoff infiltration capacity, heightening hydrological connectivity and downstream flood risks even during minor storms (<10-year return periods).

5.2.2. Modeling challenges and opportunities

Addressing these gaps requires integrating long-term maintenance impacts into hydrological models. Tools like the HEC-RAS model (Ali et al., 2007; Biazin et al., 2012) show promise for simulating interactions between runoff structures and water resources. Some examples include benches, terraces (Ben Khelifa et al., 2021), and grassed waterways (Gathagu et al., 2018), both included in the SWAT model. In these rare cases, the issue of climate change and the long-term maintenance of these structures is not addressed. A key barrier is spatial resolution: structures such as terraces or grassed waterways are often excluded from watershed-scale models due to their localized footprint. Additionally, their complex socio-hydrological functioning—involving diverse actors and adaptive practices—introduces uncertainties that challenge quantitative representation. Coupling high-resolution remote sensing with participatory monitoring could improve data granularity, while agent-based models might better capture human-natural interactions (Table 2). Prioritizing regions with high structure density (e.g., Mediterranean terraced systems, Asian paddy fields) would yield actionable insights for climate adaptation.

5.3. Application of the framework in drought-resilient planning and flood-prone regions

The proposed framework (Fig. 4) provides actionable support to co-design strategies for maintaining runoff management structures in regions confronting climate extremes, balancing drought resilience and flood mitigation.

In drought-resilient planning, the framework can guide the maintenance of structures such as infiltration ditches and micro-catchments to increase green water retention in arid and semi-arid areas such as Sub-Saharan Africa (Wolka et al., 2018). Maintenance practices such as regular desilting and repair of infiltration structures can increase sustained water infiltration capacity during dry periods. Integrating traditional knowledge—such as vegetation buffers to reduce evaporation—can also improve adaptability, aligning maintenance with local agroecological practices.

In flood-prone regions such as some Mediterranean river and stream valleys, the framework prioritizes stabilizing terraces and headwater ditches to manage intense rainfall. For example, in Italy's Cinque Terre, systematic reinforcement of dry-stone terrace walls before the rainy season mitigates collapse risks (Cevasco et al., 2013). Remote sensing tools monitor terrain changes and vegetation overgrowth, enabling proactive interventions to maintain drainage efficiency and reduce flood hazards (Fiorucci et al., 2023).

6. Conclusion

This study outlines the urgency of improving the description and understanding of maintenance for agricultural runoff management structures. The ultimate goal is to contribute to advancing the assessment of sustainable agricultural practices and environmental stewardship. We have shown how climate-driven extremes—intensifying droughts and erratic rainfall—threaten the functionality of these structures, demanding coordinated action across stakeholders with diverse roles and responsibilities (Zhang et al., 2019).

Research on maintenance is needed to bridge traditional knowledge and scientific innovation. Local practices, such as the use of specific vegetation on earthworks for evaporation control, or community-led desilting, offer context-specific solutions rooted in historical adaptation. These can be augmented by advanced modeling and remote sensing to predict degradation risks (e.g., terrace collapse, ditch occlusion) and prioritize interventions. For policymakers, the framework provides a standardized lexicon to harmonize terminology across regions, enabling the definition of interoperable databases for structured data sharing to assess socio-ecological impacts and guide spatial planning. Such standardization is critical for creating scalable, regionally adaptable policy tools and enabling global knowledge exchange.

To advance research on the sustainable maintenance of permanent runoff management structures in rainfed agriculture under climate change, we recommend five main strategies.

- Prioritizing cost-effective maintenance of high-impact structures in climate-vulnerable regions, by balancing costs of practices (i.e., the tactic level) against long-term rehabilitation needs (i.e., the strategic level). Standardized frameworks for comparative evaluation of maintenance will allow for optimization of resource allocation, including in comparison to rehabilitation or new construction.
- Advancing monitoring techniques by developing the integration of remote sensing surveys (e.g., LiDAR, Sentinel-2) with community feedback and field observation to populate structured databases that track maintenance impacts on structural integrity and ecohydrological performance.
- Extending study durations by identifying a set of minimum descriptors for maintenance practices to facilitate longitudinal data collection and interoperability, and increase the understanding of long-term effects (>15 years) in phase with climate dynamics.
- Aligning policies with long-term risk frameworks, such as the European Union Floods Directive, to institutionalize standardized maintenance protocols and incentivize synergies of public-private funding.
- Integrating frameworks to expand inter- and transdisciplinary research (1) to evaluate long-term maintenance impacts under varying climate scenarios and (2) develop scalable strategies for under-documented regions and climate-vulnerable (e.g., Mediterranean floodplains, Sub-Saharan drylands).

By standardizing terminology and maintenance criteria, stakeholders can share metrics for adaptive governance and public investment prioritization. In light of the European Directive 2007/60/EC on flood risk prevention measures, medium-term (30 years) cost-benefit analyses, incorporating investments on maintenance of structures, could inform future research directions. Structured databases derived from standardized frameworks will enhance the accuracy of these analyses, particularly under climate uncertainty. This can inform and facilitate the development of monetized approaches for rural runoff management structures emphasizing the significance of regular maintenance, before costly repairs or rebuilding. However, it is important to note that, in contrast to many studies that have been conducted under the European Flood Directive, the impact of climate change on hazard occurrence should be incorporated into these medium-term analyses.

By emphasizing the hybridization of traditional wisdom and technical innovation in the maintenance of runoff management structures, this work stresses the role of stakeholders in mitigating water scarcity and flooding while safeguarding rainfed agricultural productivity. Proactive climate-adaptive maintenance of runoff management structures is not merely a technical task but a cornerstone of global food security and environmental sustainability in an era of escalating climate volatility.

CRediT authorship contribution statement

Davide Rizzo: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Fabrice Vinatier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Conceptualization. **Frédéric Jacob:** Writing – review & editing, Funding acquisition, Conceptualization. **Intissar Ferchichi:** Writing – review & editing. **Insaf Mekki:** Writing – review & editing. **Jean Albergel:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Jean-Stéphane Bailly:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used various free online generative AI services in order to improve the fluidity and clarity of the text. DeepSeek was used to support detailed English language proofreading. The Grok 2.0 AI algorithm was used to generate the background conceptual illustration for Figs. 6 and 7. After using these services, the authors carefully reviewed and edited the content as needed and took full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare no competing interests.

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Data availability

I have shared relevant data on a web repository and attached the DOI Bibliographic search on agro-hydrological infrastructures: query design strategies and refinement process for a literature review (Original data) (Zenodo)

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