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Challenges and future opportunities

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Discussion

Sand dams for sustainable water management: Challenges and future opportunities

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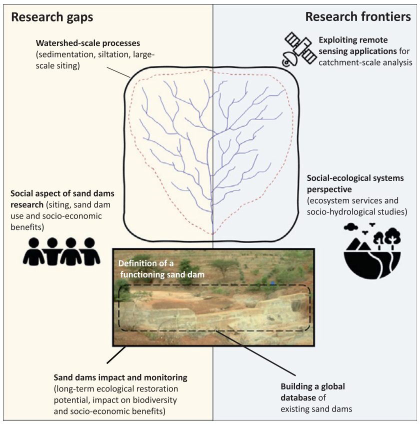
GRAPHICAL ABSTRACT



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ABSTRACT

Sand dams are impermeable water harvesting structures built to collect and store water within the volume of sediments transported by ephemeral rivers. The artificial sandy aquifer created by the sand dam reduces evaporation losses relative to surface water storage in traditional dams. Recent years have seen a renaissance of studies on sand dams as an effective water scarcity adaptation strategy for drylands. However, many aspects of their functioning and effectiveness are still unclear. Literature reviews have pointed to a range of research gaps that need further scientific attention, such as river corridors and network dynamics, watershed-scale impacts, and interaction with social dynamics. However, the scattered and partially incomplete information across the different reviews would benefit from an integrated framework for directing future research efforts. This paper is a collaborative effort of different research groups active on sand dams and stems from the need to channel future research efforts on this topic in a thorough and coherent way. We synthesize the pivotal research gaps of a) unclear definition of "functioning" sand dams, b) lack of methodologies for watershed-scale analysis, c) neglect of social aspects in sand dam research, and d) underreported impacts of sand dams. We then propose framing future research to better target the synthesized gaps, including using the social-ecological systems framework to better capture the interconnected social and biophysical research gaps on sand dams, fully utilizing the potential of remote sensing in large-scale studies and collecting sand dam cases across the world to create an extensive database to advance evidence-based research on sand dams.

1. Introduction

Anthropogenic pressure on water resources has never been higher (HLPW, 2018; Leal Filho et al., 2022; UNESCO and UN-Water, 2020) and the increasing world population requires ever more water to satisfy its needs (FAO, 2020). Hence, water scarcity, defined as the imbalance of water demand and supply, and water shortages caused by a sudden lack freshwater are major challenges that humanity must urgently tackle (FAO, 2020; UNCCD and FAO, 2020). Drylands which cover 46.2% of the global land and are inhabited by approximately 3 billion people (IPCC, 2019) are particularly susceptible to these threats (Koch and Missimer, 2016; UNCCD, 2017) because of high evaporation losses (Stewart and Peterson, 2015) and climate change impacts (Huang et al., 2017).

Despite these major challenges, solutions to water scarcity do exist. For example, irrigation assessments at the global (e.g. Neumann et al., 2011; Rosa et al., 2020) and continental scales (e.g. Altchenko and Villholth, 2015; Amjath-Babu et al., 2016; Xie et al., 2018; You et al., 2011) show that the potential for expanding irrigation is significant in some dryland regions, including sub-Saharan Africa. Among the water resources supporting this potential are "sand rivers", which are shallow alluvial aquifers and represent a natural water storage phenomenon easily accessed by local populations in drylands (Singh and Chudasama, 2021). Although quite common in drylands, particularly in Africa, the water resource hidden in sand rivers remains largely unexploited in the framework of national- and regional-scale water development programs, for example current estimates show they could supply 16,000 ha of irrigated lands around the Mzingwane river in Zimbabwe and the Lower Limpopo in Mozambique (Duker et al., 2020). This potential is well known to local people, but a sound and effective action to invest in the improvement of these types of nature-based storage systems is needed to make the best use of such a fundamental resource (Duker et al., 2020).

The water yield of sand rivers can be enhanced by constructing small-scale hydraulic retention structures across the riverbed (de Trincheria et al., 2018; Lasage et al., 2008, 2015; Nilsson, 1988). Such structures, commonly termed "sand dams", are impermeable walls which collect the transported sediments during intense rainfall (Neufeld et al., 2021) (Figs. 1, 2.a and c). Over the rainy season, sand carried by the river is deposited behind the wall and accumulates until it reaches the top of the dam (sand dam maturation). By storing water in the pores of the sand, evaporation losses are reduced, resulting in a greater quantity of water than similar-sized surface water reservoirs (Lasage et al., 2015). Water quality is also improved because the sand acts as a slow sand filter (Lasage et al., 2015; Quinn et al., 2018). Sand dams are constructed for numerous reasons, such as supporting infrastructure for road crossings and generating sand-filled areas suitable for excavating shallow wells for animal watering (Excellent Development, 2019; Neal, 2012). However, the most common purposes are managed aquifer recharge and local water storage (Lasage et al., 2015; Zhang et al., 2020).

The performance of sand dams is commonly assessed on both social and environmental benefits. Water is typically accessed in two ways, either via a scoop hole upstream the dam or by an adjacent handpump often dug into the underlying aquifer (Fig. 2.b). If the abstraction is carefully managed, the remaining sand-stored water can be beneficial for increasing groundwater levels and growing the surrounding vegetation. However, the trade-off between these differing outcomes needs to be examined when constructing a dam to ensure that the local community's expectations are met (Quinn et al., 2019). The specific topography of the construction sites also needs to be accounted for as very steep and high riverbanks may allow only

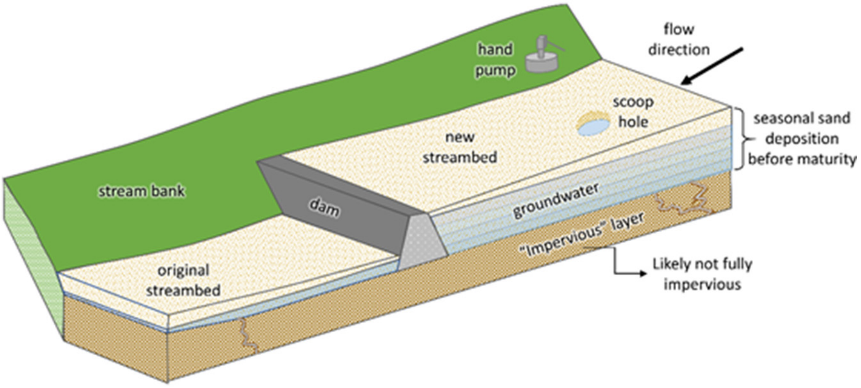

Fig. 1. Scheme of a sand dam.
Adapted from Ritchie et al. (2021).

Fig. 2. Pictures of sand dams: (a) sand dam in May Gobo (Ethiopia) and scoop holes (b); (c), (d) sand dams in Kenya.
Sources: (a) and (b) – photo -by Lorenzo Villani; (c) and (d) Excellent Development - (CC BY-NC-ND 2.0).

water withdrawals from the sand river, while shallow banks (flood plains) permit subsurface irrigation opportunities in the nearby areas.

The study of sand dam technology has experienced a renewed interest in recent years (Eisma et al., 2021; Eisma and Merwade, 2021, 2020; Ertsen and Ngugi, 2021). Previous literature reviews have summarized current knowledge on the topic, pointing to a range of research gaps that need further scientific attention (Ritchie et al., 2021; Yifru et al., 2021). These reviews mainly focus on the hydrology, water quality (Ritchie et al., 2021) and the planning and implementation of the structures (Yifru et al., 2021), pointing to the need for more long-term watershed-scale analysis and climate change assessments. However, gaps in our understanding of sand dam performance still exist, including the river network- and watershed-scale environmental effects of sand dams, and their interaction with social dynamics. Models predicting the impact of watershed dynamics on sand dams are missing, together with adequate information and analyses on how stakeholders and communities adapt water resources and watershed management after the construction of a sand dam. Furthermore, while all the recent literature on sand dams is seeking more integrated studies on the structures, a clear indication of the future research areas to be prioritized is lacking, together with an identification of suitable and innovative methodologies to address the most relevant research gaps.

This paper is the result of a collaborative scientific dialogue between several research groups currently active in the fields of water harvesting and sand dam research with the aim of presenting a coherent and collaborative strategy to address the open research gaps on sand dams. The specific goals of the present work are to a) prioritize existent research gaps, b) identify innovative research frontiers and c) provide a clear research pathway forward to understand the performance and prevalence of sand dams across the world.

2. Methodology

Following the analysis of existing scientific literature, the absence of a clear identification of sand dam research priorities and their benefits was highlighted. To address this absence, a collaborative effort was initiated by the Water Harvesting Lab[1] at the University of Florence, with the aim of structuring a discussion on how to classify and analyze existent research gaps and identify possible future research directions. Based on the experience of other collaborative commentary papers (Blöschl et al., 2019), the methodology of the work was based on a series of sessions, held within a one-day workshop.

A workshop, titled "Framing and consolidating research on Sand Dams" was organized online on May 7th 2021. The participants of the workshop were selected based on the production of peer-reviewed journal articles indexed o Elsevier's SCOPUS database in the last 10 years and were contacted to take part in the workshop. Invited participants were also asked to extend the invitation to other scholars they considered experts on the topic.

The workshop was organized in two sessions: In the first one, all the participants were asked to share their latest research outputs and their opinion on the most relevant open research questions on sand dams. Notes were made about the research questions expressed by all the participants in a collaborative online dynamic document to aid discussion and brainstorming.

In the second session, research questions collected in the first session were discussed among the participants, with the aim of reaching an agreement on substantive research gaps. The dynamic document was used as a support and the questions were then organized and grouped into four macro-groups of research gaps (see Section 3).

The writing process was organized by developing an in-depth analysis of research gaps, with a mixed group of experts involved in writing specific sections of the paper based on their expertise. Expanding from the research gap analysis, the space for new research approaches was defined by focusing on the scientific analysis of sand dams (research frontiers) as a tool of sustainable management and climate change adaptation (Fig. 3).

3. Results and discussion

During both collective and dedicated discussions, the following research gaps were prioritized as they were considered the most relevant, and the most commonly identified during the participatory workshop.

1. Definition of a functioning sand dam
2. Watershed-scale analysis: watershed-scale processes, sedimentation, siltation, and sand dam siting
3. Social aspect of sand dam research
4. Sand dam impacts and monitoring

3.1. Defining and assessing sand dam functionality

Despite the general tendency to think of sand dams as 'successful or not', their performance is increasingly recognized to be a spectrum (de Trincheria et al., 2018; Ngugi et al., 2020). Some perform at extremely high levels providing water to their local community throughout the dry season. Others never fully mature or fill with fine particles such as silt or clay rather than sand, and thus provide little to no usable water. As recorded by Ngugi et al. (2020), sand dams exist at nearly every interval between these two extremes. This recent acknowledgment of variable sand dam performance has prompted examination of sand dam functioning (Eisma and Merwade, 2020; Neufeld et al., 2021; Ngugi et al., 2020; Quinn et al., 2019). However, the question remains — how should sand dam functioning be defined? Answering this question can guide the selection of appropriate indicators to assess the performance of sand dams in a structured way.

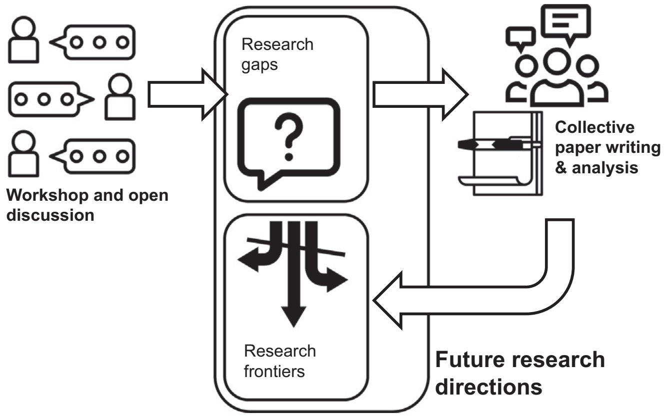

Fig. 3. Paper methodology.

We propose that the functioning of sand dams should be assessed relative to their initial purpose, as defined by the communities in which they are built and the organization supporting construction (see Table 1). Three overarching purposes have been identified for sand dams: (1) groundwater recharge (without direct groundwater exploitation by the community near the sand dam – e.g. scoop holes in the riverbed), (2) community water use, and (3) ecological restoration. For sand dams built for groundwater recharge, functioning should be assessed based on the magnitude of water table rise, including consideration of the spatial extent and duration of impact. Other related factors deserving consideration include short and long-term impacts of the raised water table and the local and regional importance of the recharged aquifer. When sand dams are built to provide a water resource to a community, functioning should be assessed based on the number of households served, the duration of support and water quality improvement. This will be impacted by a variety of additional factors including, but not limited to, water use (agricultural, domestic, etc.), other nearby water sources, and local rainfall patterns. Lastly, sand dams

Table 1
Proposed assessment standard for sand dam functionality.

Purpose	Indicators	Additional considerations
Groundwater recharge[a]	• Water table rise and areal extent • Water volume recharged per unit of time	• Cascading bio-geophysical impacts (vegetation, land subsidence, etc.) • Cascading human impacts (agriculture, greenhouse gas emissions, etc.)
Community water resources	• Number of households served • Increased duration of water supply • Improved water quality	• Analysis of the water use (domestic, agriculture, livestock, etc.) • Presence of alternative water sources (springs, boreholes, rainwater) • Unimodal or bimodal rainfall (i.e., annual inter-seasonal pattern) and flooding regime
Ecological restoration	• Increased biodiversity • Enhanced Normalized Difference Vegetation Index (NDVI) of riverbanks	• Increased availability and use of natural resources.

[a] Without direct groundwater exploitation by the community nearby the sand dam.

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[1] https://www.dagri.unifi.it/vp-261-wh-lab.html.

constructed for ecological restoration should be assessed based on the increase in local biodiversity. Water has one of the strongest impacts on abundance and movement of wildlife (Naidoo et al., 2020) and water resources in drylands have increased wildlife visits during the dry season (Lundgren et al., 2021). Dryland water resources also support increased germination of local flora (Lundgren et al., 2021), further supporting the idea that biodiversity is a strong indicator of sand dam functioning. Such indicators can either be used to assess the functionality of a single sand dam, or a group of sand dams built in series. In this latter case, the application of the criteria in Table 1 to each of the sand dams in the series can reveal if one of these is performing worse than the others due to upstream-downstream dynamics, poorer local conditions, and/or design and construction inconsistencies.

3.2. Watershed-scale processes – hydrology, sedimentation, and siltation

Hydrological modelling of sand dams has focused mainly on local dynamics (infiltration, seepage, etc. - Quilis et al., 2009; Quinn et al., 2019), while watershed-scale modelling has been understudied. Early work done by Forzieri et al. (2008) conducted preliminary hydrological analysis using considerable assumptions (neglecting soil infiltration capacity and assuming uniform distribution of precipitation) to inform sand dam siting. These early efforts exhibit the potential of scientific analysis to improve sand dam siting, but they are still at an initial stage.

So far, only one peer-reviewed study has been published that uses watershed-scale hydrological modelling to support best practices for sand dam siting or construction, where Eisma et al. (2021) used an integrated hydraulic and hydrologic model of a watershed with three cascading sand dams to examine how land cover, soil texture, and climate factors impacted sand dam performance metrics. This first attempt at applying hydrologic modelling to sand dam siting found that sand dams are better suited in watersheds that are cultivated (in the absence of erosion), sandy, and with a bimodal rainfall pattern. However, in the presence of soil erosion processes in cultivated lands can result in soil loss, causing siltation.

Overall, it should be highlighted how sand-dams are small-scale structures, and that, in most cases, it may be sufficient to simulate the full hydrological watershed with simple 1D equations while using a more detailed 2D representation of surface and vadose-zone water flows in the vicinity of the dam (Eisma et al., 2021).

Sediment dynamics at the watershed scale are even more important for assessing the correct siting of sand dams since the time needed for creating the upstream sand reservoir and the sediment composition determine when and how the sand dam will be effective. In this sense, however, few studies have been carried out since the classical work of Wipplinger (1958). Baurne (1984), Ertsen et al. (2006), Gijsbertsen (2007), de Trincheria et al. (2015, 2016, 2018), Viducich (2015), Quinn et al. (2019) and Neufeld et al. (2021) have worked on the relationship between sedimentation and the performance of sand dams. Concerns have been raised around dam structures' ability to collect coarser particles, with siltation (accumulation of clay and smaller particles) being observed at numerous sites (de Trincheria et al., 2018). Methods for minimizing siltation, before project completion, exist, such as terracing surrounding land and constructing the dam across numerous wet seasons (Tiffen et al., 1994); however, it is unclear to what degree these practices are implemented. In addition, current site selection methods, such as examining whether coarse sand is present in the riverbed may be misleading as land use and land cover can change, resulting in erosion and thus increasing the silt present in the ephemeral rivers (Nissen-Petersen, 2011). Few studies have been completed to assess the sediment of existing sand dams. For example, Neufeld et al. (2021) examined the core samples from 97 dams across southern Kenya; they found that although clay and silt were present across all sites, most particles were sandy. However, they estimated that siltation reduced water storage up to 25%, potentially reducing yield from the sand dams by tens of thousands of liters per year. Watershed hydro-sedimentological modelling and erosion analyses, namely the use of watershed scale model to estimate water flows, and erosion-led sediment inputs at a sand dam point, are potential approaches for closing the research gap related to sedimentation and siltation. However, so far, no studies have estimated the time needed for a sand dam to reach maturity based on the watershed characteristics.

3.2.1. Site suitability analyses

Several studies have focused on locating and ranking potential sites for sand dams and other water harvesting structures using spatial decision support systems, based on both physical (e.g. type of soil, land cover, slope) and socio-economic parameters (e.g. distance to settlements, cultivated areas, etc.). These approaches have the advantage of being inexpensive and relatively easy and fast to apply. In their research, Ngugi et al. (2020) used overlay analysis to evaluate existing siting criteria with attributes of sand dams that successfully retained water during the dry period for 116 dams in Kitui County, Kenya, finding consistent patterns for rainfall amount, water indicating vegetation, percentage of clay in soils, stream order and agro-ecological zone; while Forzieri et al. (2008), used a multi-attribute decision method and classification approach to identify coarse geomorphic and hydrological indicators for dam sites in Kidal, Mali. Outside of the peer reviewed literature, organizations have used overlay analysis and weighted criteria to shortlist sites for in-situ survey, such as Excellent Development in Eswatini (Ryan, C., pers. comm, 2021), Dabane Trust in Zimbabwe (Ngwenya, N., pers. comm, 2021), and the World Bank in Somalia and Angola (Limones, N., pers. comm, 2021). More examples are likely to have occurred but have not been documented or shared widely.

Despite the findings from these studies, considerable uncertainty remains on the most appropriate criteria for large-scale studies on sand dam siting. Like other river basin-scale models, the main problem for the application of these techniques is the scarcity of input data in remote arid and semi-arid environments, which makes certain simplifications and assumptions necessary. Many assumptions that must be used produce a more conservative approximation of water resource and sediment availability (Love et al., 2011). Another possible development in sand dam siting studies is related to the adoption of specific siting algorithms for different sand dam uses. For instance, while in most cases, sites with a shallow bedrock depth and stony banks present the best siting options, different criteria may be adopted if the goal of sand dam implementation is recharging the riverine and/or the riparian aquifer (Eisma and Merwade, 2021).

At a local scale, checking the adequacy of the specific river sections for sand dam suitability requires high-resolution spatial data that captures site-specific information (e.g. depth of the bed rock, slope of the river banks etc. - Gijsbertsen, 2007), which are rarely available in drylands, posing an additional challenge to a thorough siting procedure with GIS tools, especially for large-scale suitability analysis.

3.3. Social aspects of sand dam research

3.3.1. Sand dams' exploitation

Sand dams are most often built with support from non-governmental organizations (NGOs) for the benefit of the entire community (Ngugi et al., 2020) but are sometimes exploited for individual gain. Examples of sand dam exploitation that warrant further study include: (1) sand harvesting, (2) control of abstraction by individuals within the community, (3) excessive water abstraction methods, and (4) granting of riparian zone farming rights.

Sand is an important construction material, and sand dams are constructed in sandy riverbeds that can source sand for the construction industry. The practice of selling sand from the riverbed may either decrease water storage capacity or may disincentivize the construction of sand dams in downstream locations (Leal Filho et al., 2021). Further, while sand dams are meant to be a community resource, this is not always well-understood by communities, which may provide an opportunity for a small local subset to seize control of the sand dam for personal use or to sell the water. For example, Hut et al. (2008) noted the use of a diesel pump by some members of the community to extract excessive amounts of water from the sand dam, receiving significantly more benefits at the expense of the larger community. While pumps improve access to the water stored in sand dams, their use for water abstraction must be equitably managed.

A more complex and interdisciplinary problem concerns the granting of riparian zone farming rights (Hodgson, 2016). The socio-cultural dynamics around land tenure and management systems are often neglected by the scientific community investigating the use and impact of sand dams. Experiences of local NGOs note how the members of community groups in charge of managing sand dams are often the same members having land rights on the farming area near the sand dams, which can be irrigated more easily. Depending on the customary land tenure system, some people may be favored (e.g. the head of the village, the most powerful family or wealthier farmers). This issue is of great impact on the final beneficiaries of the sand dams but is an under-studied exploitation practice that may provide insight into the socio-economic dynamics surrounding sand dams.

3.3.2. Community involvement: maintenance and participatory siting

With respect to maintenance, generally water resources infrastructure funded by third-party donors do not get repaired when they fail, and sand dams appear to follow this trend (Ertsen and Ngugi, 2021). Introducing a new technology to communities with no experience, exposure, or clear understanding of the mechanisms, represents a major barrier to its long-term adoption (Piemontese et al., 2021). Sand dams must be planned and implemented with a careful and thorough engagement and participation of the local communities to ensure that they understand and take ownership of the technology, leading to a long-term beneficial result. However, many NGOs have minimal contact with communities after sand dam construction is complete – often due to short-term funding schemes – (Cruickshank and Grover, 2012), and so maintenance training and follow-ups are limited. Integrated social-ecological research may identify why communities do not perceive the failure of the sand dam as a loss to their environment, economic wellbeing, and health.

While some sand dams' failures can be addressed by post-construction efforts, other sand dams fail because of improper design for which repair efforts would be futile. The scientific study of sand dam failure remains limited, with the first extensive work published by Ngugi et al. (2020). Despite the efforts of Ngugi et al. (2020) to link sand dam failure to the watershed features, many questions remain. In addition to this, NGOs rarely publish or publicly discuss the failures of sand dams, so hard data is limited and there is extensive debate and opposing perspectives in the literature (e.g. de Trincheria et al., 2018). Other important questions remain regarding (1) the physiographic factors leading to sand dam failure, (2) inadequate surveys and insufficient study of environmental conditions and sand dam construction techniques, (3) factors impacting the decision to repair the dam, and (4) identification of an acceptable failure rate and whether this should consider solely cost/benefit analysis or must include the impact of a failed dam on communities.

More generally, guidelines and scientific studies for the best siting of sand dams highlight the importance of participation as a key approach to building sand dams with local communities (Grigg, 2016; Ngugi et al., 2020). However, most of the literature on sand dams comes from hydrological, engineering, and ecological studies, which usually focus on technical aspects, leaving the socio-cultural aspects out of the picture. More research is needed to understand the socio-cultural factors influencing the adoption, use, maintenance, and functionality of sand dams. Although these socio-cultural dynamics are fundamental for the usefulness of sand dam projects, the siloed scientific approach and the focus on the technology alone have driven most of the research on sand dams so far. During the workshop and follow up discussions, the author team proposed several topics that require thorough integration of socio-cultural research to better understand i) *integrating local knowledge into identification of suitable sites*, ii) *balancing communities' needs and expectations to avoid conflicts*, iii) *donor conditions and political and administrative leaders' interference and effect on dam siting and functionality*.

3.4. Assessing sand dam performances

Monitoring of water balance, water quality and the environmental effects of sand dams is sporadic, limited to individual dams and case study sites, and only for a few years after construction (Eisma and Merwade, 2020; Quinn et al., 2019). Overall, the main objective of the structures is to enhance water availability from sand rivers, improving communities' socio-economic conditions and livelihoods especially in the dry season and during periods of extreme drought (Lasage et al., 2015). Households tend to move towards higher water consuming activities because of increased water availability. In areas with sand dams, average water consumption per household was about 440 l/day compared to 110 l/day in areas without sand dams (Lasage et al., 2008). This effect is an important factor when considering upscaling sand dams to larger areas. For example, Aerts et al. (2007) showed that in an area with a projected 500 to 1500 sand dams, water storage as a percentage of the total annual available water would increase from 3 to 20% under future climate change. Lasage et al. (2015) confirmed such an effect in the dry months in Ethiopia (April and September), and low flow occurrences (Smakhtin et al., 2006) would rise from 18% to, respectively, 23% and 27%. More research is thus needed to assess the potential limits of upscaling of sand dams, and to avoid reduced runoff downstream in the dry season, possibly considering watershed-scale hydrological and socio-economic dynamics (e.g. Bouma et al., 2011).

Despite the evident increase in production, a holistic approach to performance assessment is needed, because other recurrent challenges of smallholder farmers, such as low soil fertility or market and credit access can still represent a barrier for livelihoods' improvement (Duker et al., 2020). Irrigation efficiency and water productivity are typically low in sand dam irrigation schemes (Villani et al., 2018), even though it is not clear if improving efficiency would lead to "real" water savings (van Opstal et al., 2021), since a share of the water applied returns to the sand dam aquifer. Nevertheless, evaporation is very high; hence, improved irrigation systems are needed.

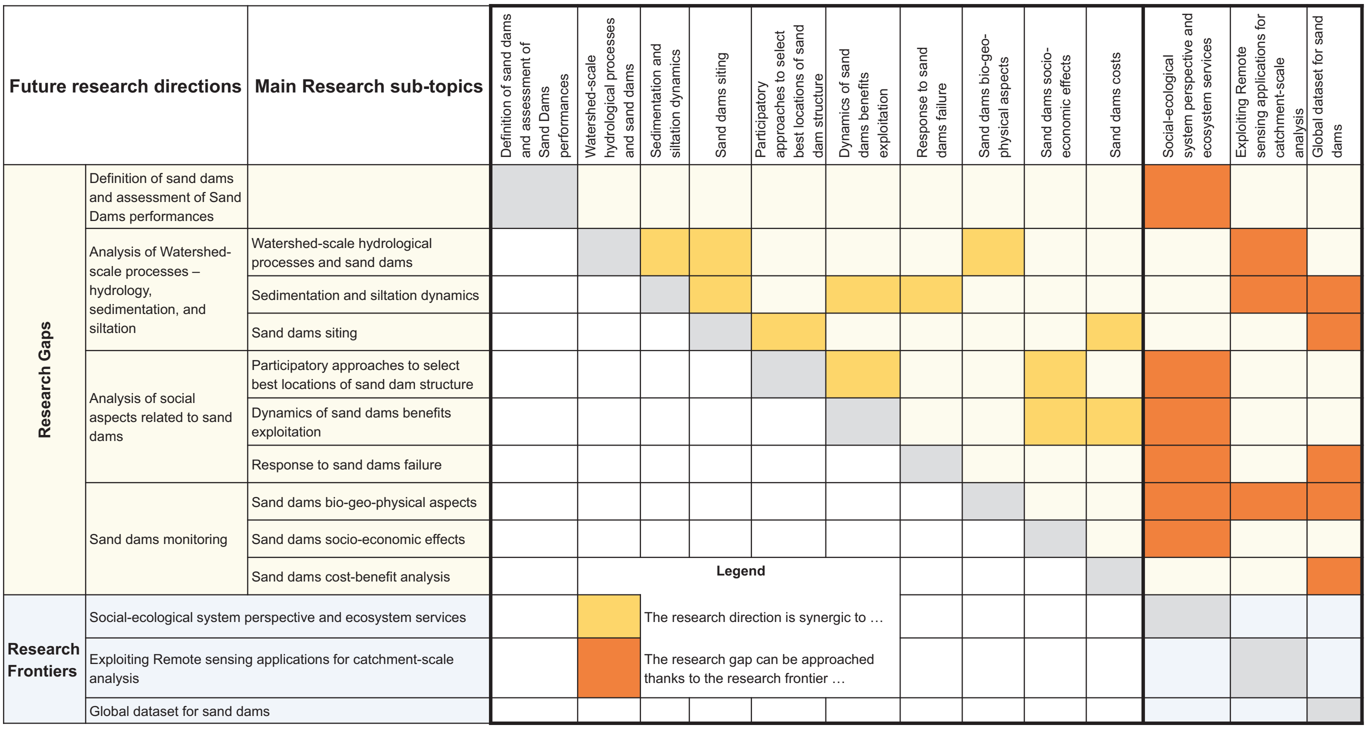
There is still much uncertainty about the socio-economic effects of sand dams. The sparse research shows that sand dams have positive effects on communities' well-being. However, unintended consequences of irrigation, such as the spread of malaria and the shifting away from food crops need to be considered (Ritchie et al., 2021). The long-term sustainability of sand dams under climate change and other socio-economic developments needs further enquiry. Such studies would support the choices in managing water security and to optimize the development and use of sand dams (Ritchie et al., 2021). Finally, more longitudinal survey studies in areas both with- and without sand dams are needed to assess the socio-economic effects of sand dams and how water quality and water availability impact livelihoods, wealth, gender issues and education.

3.5. Future research frontiers and opportunities

We propose three approaches to support a targeted and coherent research effort in advancing knowledge on sand dams (Research Frontiers). The Research Frontiers were conceived to address the current research gaps, but they could also be considered as standalone topics (Fig. 3). We define the combination of Research Gaps and Research Frontiers as "Research Directions" for sand dams (Fig. 3).

3.5.1. Social-ecological system perspective and ecosystem services

The gaps identified across the phases of sand dam implementation present an interdisciplinary challenge. From sand dam siting to the definition of a functioning dam, the socio-economic and biophysical aspects of the project need to be carefully integrated. Addressing these gaps in siloes is neither appropriate nor sufficient, given the complex and intertwined links between the socio-economic and environmental aspects of development



Future research directions		Main Research sub-topics	Definition of sand dams and assessment of Sand Dams performances	Watershed-scale hydrological processes and sand dams	Sedimentation and siltation dynamics	Sand dams siting	Participatory approaches to select best locations of sand dam structure	Dynamics of sand dams benefits exploitation	Response to sand dams failure	Sand dams bio-geo-physical aspects	Sand dams socio-economic effects	Sand dams costs	Social-ecological system perspective and ecosystem services	Exploiting Remote sensing applications for catchment-scale analysis	Global dataset for sand dams
Research Gaps	Definition of sand dams and assessment of Sand Dams performances		▨										🟧		
	Analysis of Watershed-scale processes – hydrology, sedimentation, and siltation	Watershed-scale hydrological processes and sand dams		▨	🟨	🟨				🟨				🟧	
		Sedimentation and siltation dynamics			▨	🟨		🟨	🟨					🟧	🟧
		Sand dams siting				▨	🟨					🟨			🟧
	Analysis of social aspects related to sand dams	Participatory approaches to select best locations of sand dam structure					▨	🟨			🟨		🟧		
		Dynamics of sand dams benefits exploitation						▨			🟨	🟨	🟧		
		Response to sand dams failure							▨				🟧		🟧
	Sand dams monitoring	Sand dams bio-geo-physical aspects								▨			🟧	🟧	🟧
		Sand dams socio-economic effects									▨		🟧		
		Sand dams cost-benefit analysis										▨			🟧
Research Frontiers	Social-ecological system perspective and ecosystem services												▨		
	Exploiting Remote sensing applications for catchment-scale analysis													▨	
	Global dataset for sand dams														▨

Legend

🟨 The research direction is synergic to …

🟧 The research gap can be approached thanks to the research frontier …

Fig. 4. Synergies among the different future research directions for sand dams. It can be shown as (for instance) the study of sedimentation and siltation dynamics (line 3) can be synergic to the study of watershed dynamics, sand dam siting, of the dynamics of sand dams benefits exploitation, and of the response to sand dams failure. It can be approached with remote sensing analysis and by studying the data on the global database on sand dams.

programs, that are the primary mechanism by which sand dams are built (Fig. 4).

A consolidated research approach for understanding the complexity of sustainability-related problems and solutions is represented by social-ecological systems (SES) research (Folke, 2006). SES are systems shaped by the complex interplay between nature, economics, and society, which constitute the core unit of study in sustainability science research (Folke et al., 2016). The SES framework has been used to understand and address agricultural and water sustainability issues from the farm to the global scale (Lescourret et al., 2015; Moraine et al., 2017; Piemontese et al., 2020). Framing sand dams as SES can provide a valuable integrated approach to address multiple research gaps, as identified in this work. A SES framework to sand dams could concretely help provide a more comprehensive assessment of the impacts of sand dams considering both the ecological and the socio-economic indicators, revealing potential trade-offs or enhancing positive mechanisms between the socio-economic and the ecological dimensions that are normally overlooked by narrow disciplinary assessments. For example, Di Baldassarre et al. (2015) show how considering an integrated system of hydrological and socio-economic dimensions can reveal the counterintuitive mechanisms of increasing long-term flood risk, because of the construction of flood-containing dams. The SES framework can also be useful to evaluate positive feedbacks related to the engagement of communities in natural resources management and can similarly be applied to sand dam studies (Nagoli and Chiwona-Karltun, 2017). Another practical assessment is provided by Piemontese et al. (2020), who used SES framing to provide context-specific estimates of the potential impact of water harvesting technologies on food production across regions with different social-ecological conditions.

Within the SES framework, ecosystem services can represent a practical tool to quantify the potential impact of sand dams on the environment and on people (MEA, 2005). This tool has been applied to evaluate the multiple benefits of different water harvesting structures, such as small dams (Dile et al., 2016; Mastrorilli et al., 2018), highlighting both the effects of a single structure and multiple cascading systems. This latter approach is especially useful for a context with a high density of sand dams (e.g. Kitui County, Kenya). The Ecosystem Services approach simultaneously allows the isolation and valuing of the different direct and indirect benefits of sand dams, including increased water availability for people, livestock and agriculture, groundwater recharge, increased vegetation cover, availability of sand as a construction material. This research appeared to be particularly timely, given the momentum imposed by the UN Decade for Ecosystem Restoration for 2021–30. Barriers in applying both approaches include the availability of detailed input data, which are discussed in other sections of the paper.

3.5.2. Exploiting remote sensing applications for watershed-scale analysis

Advances in high-resolution geospatial information, obtained from remote sensing analysis or modelling have increased the range and the quality of physical factors to define site suitability in the absence of field data and monitoring networks. In general, there is increasing interest in exploring how big data analytics and big data platforms can be used to support investigations of groundwater dynamics and groundwater development and management (Gaffoor et al., 2020). For example, surface water detection based on Sentinel-2 (Walker et al., 2019), or the application of the Global Surface Water Explorer based on Landsat images facilitates incorporation of the frequency and dynamics of water occurrence to the screening of potential sites. Similar analyses were performed in a recent project by the World Bank (Limones, N., pers. comm, 2021). In any case, as pointed out by Ertsen and Hut (2009), modelling to find sand dams sites should not be directly and blindly replicated in any region. The selection process needs to be reviewed and refined carefully, adapting to the available field data and, most importantly, to the essential criteria in each candidate area like socioeconomic parameters. These analyses offer a relatively straightforward approach for narrowing the area subject to ground validation. However, investments in the development of sand dams must always be preceded by visual interpretation of satellite imagery and detailed field investigations of the candidate sites. This is the case of the topographic evaluation, the geomorphological suitability analyses, or the water sources census of the candidate areas to check water levels or salinity of the aquifers. Scientific-technical advances can reduce budget and time allocation in these stages too. The incorporation of airborne observation surveys and unmanned aerial systems is being explored to increase the spatial resolution of geospatial products in related studies (Futurewater, 2017; Hassan-Esfahani et al., 2017; Manfreda et al., 2018).

Remote sensing can also play a central role in monitoring the success and performance of sand dam projects. Several projects used the Normalized Difference Vegetation Index (NDVI) based on optical data such as the Moderate Resolution Imaging Spectroradiometer (MODIS) (Eisma and Merwade, 2021). MODIS has a spatial resolution of 250 m which limits the granularity with which the impact of sand dams on the local vegetation can be observed. NDVI information based on Landsat TM and ETM with a spatial resolution of 30 m has shown to be more suitable for the observation of smaller sand dam projects (Neufeld et al., 2021; Ryan and Elsner, 2016) and data from the recently launched European Sentinel-2 twin satellites offer an even better spatial resolution of up to 10 m. In addition to these, advanced datasets like the Gravity Recovery and Climate Experiment (GRACE) can also be used to estimate increased groundwater storage induced by sand dams by gravimetry remote sensing data (Eisma and Merwade, 2021).

A separate and similarly promising development in remote sensing research is the availability of cloud-based data processing tools, such as Google Earth Engine (GEE). GEE provides analysis-ready access to vast amounts of data, including several decades of imagery of the Landsat satellite programme (Amani et al., 2020; Gorelick et al., 2017). Several new global databases were recently developed using GEE, such as the Global Surface Water Explorer. It quantifies the location and temporal distribution of water surfaces in 30 m resolution at global scale for the past three decades, using three million Landsat satellite images (Pekel et al., 2016). Initial attempts to apply the capabilities of GEE to monitoring the impact of water harvesting interventions such as traditional check dams/Jessour are promising (Castelli et al., 2019; Castelli and Bresci, 2019).

Apart from monitoring and evaluating the performance of individual sand dams or projects, the added value of remote sensing approaches is the potential of covering large areas, thus providing a key tool for case comparison, large scale assessment studies and generalized cross-regional understanding of the subject. This is a key aspect given the local/regional nature of current understanding of sand dam use and effectiveness. However, large spatial-scale remote sensing analyses are not to be considered as a panacea. Satellite products still need to be properly calibrated and checked with local data to provide reliable analysis and this could be a challenge in remote areas, where sand dams are particularly needed and implemented. Moreover, overreliance on satellite analyses could encourage top-down interventions that should instead be carefully planned, considering in-field analysis of the needs and perceptions of the local population. In this direction, new methodological approaches are needed for combining top-down remote sensing applications with bottom-up participatory work, especially on sand dams siting and performance assessments.

3.5.3. Building a global dataset for sand dams

Many of the challenges identified in this paper, such as sand dam monitoring or the analysis of sand dam costs and benefits, point to a major data gap, which calls for further field research. Particularly important is expanding the geographical boundaries of field research beyond the core region of Kitui County in Kenya and the more general East-African cluster, where the current scientific knowledge on sand dams has been developing along with NGO dissemination efforts. For example, Southern Africa is an underexplored area with a few application and research cases on sand dams (Hartley, 1997; Hellwig, 1973), which could provide complementary information on the feasibility of sand dams in African drylands. Other areas like India and the Middle East are known to host sand dams or similar structures, but the lack of standardized reporting and scientific studies make it difficult to estimate the actual spread and relevance of these applications. Also, many rural areas host some community-built structures, which might be sand dams, check dams or something similar (Balooni et al., 2008).

The lack of a standardized accounting of sand dam cases globally represents a knowledge gap in itself. We currently do not know exactly where sand dams have been tested and implemented, which makes it difficult to assess their relevance and to plan for further field research and narrow the knowledge gap. Compiling a global database would also enable comparison across different SES (or cross-regional comparison) and advance the context-specific understanding of i) the criteria for site selection (best-siting), ii) the performance and iii) the social-ecological impact of sand dams. A global database could, therefore, provide a large-scale understanding of the potential and limitations of sand dams to contribute to regional, national and global water and food security targets, to achieve sustainable livelihoods in drylands. A complete database would require a standard set of information, including the location, the coordinates, the year of construction, the year of the assessment, the name of the constructor, the name of the stream, the purpose of the dam, the way in which water is accessed, a measure of performance (see Table 1), the physical dimensions of the dam, some indicators of water quality (pH, salinity, coliforms), etc. Sources of the database might be diverse, such as research papers (e.g. Ngugi et al., 2020; Ryan and Elsner, 2016), field reports from implementing NGOs or national and international agencies, and even crowdsourced data (similar to the WOCAT database - https://www.wocat.net/en/global-slm-database/). The management of the database could be assigned to a standing institution, such as IGRAC for their Managed Aquifer Recharge database (https://www.un-igrac.org/special-project/mar-portal), while the consistency and correctness of data sent should be regularly checked, even supported by field missions to randomly sampled sand dams added to the database, by local sand dams experts coordinating with the managing institution.

4. Conclusions and outlook

Gaps in sand dam research are mainly related to sparse information regarding social dynamics connected to sand dam exploitation, limited knowledge about watershed-scale dynamics related to sand dams, and an absence of frameworks for the long-term monitoring of such water harvesting structures. An SES perspective, based on the concept of ecosystem services to rural communities, would assist in the analysis of the social dynamics related to sand dams (their impacts, and the dynamics of exploitation by rural populations) but would also improve the existing frameworks for sand dam evaluation, moving to a more integrated assessment of the performances of sand dams themselves. To address research gaps represented by watershed-scale dynamics and sand dams monitoring, we propose extending the use of remote sensing for sand dams and watershed dynamics evaluation and the creation of a global database of sand dams. This proposed future research directions represent a community vision of the next steps in sand dam research, in different contexts and at different scales, with a multi-disciplinary approach aimed at shaping a more coherent and structured scientific effort on these topics, which is key to tackling the impact of climate change and water scarcity in arid and semi-arid lands.

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