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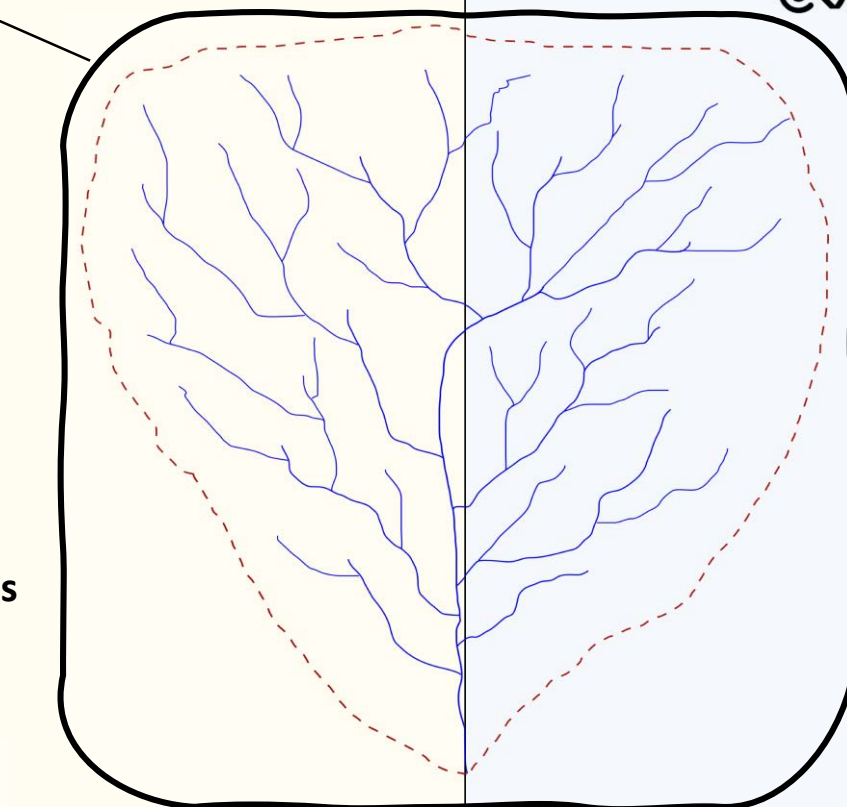
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Research gaps

Watershed-scale processes
(sedimentation, siltation, large-scale siting)

Social aspect of sand dams research (siting, sand dam use and socio-economic benefits)



Research frontiers



Exploiting remote sensing applications for catchment-scale analysis

Social-ecological systems perspective
(ecosystem services and socio-hydrological studies)



Definition of a functioning sand dam



Sand dams impact and monitoring
(long-term ecological restoration potential, impact on biodiversity and socio-economic benefits)

Building a global database of existing sand dams

1 *Title page*

2 ***Sand dams for sustainable water management: challenges and***
3 ***future opportunities***

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29 ***Sand dams for sustainable water management: challenges and***
30 ***future opportunities***

31 **Abstract**

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

51 **Keywords:** drought, water harvesting, arid and semi-arid lands (ASAL), sandy rivers

52 **1. Introduction**

53 Anthropogenic pressure on water resources has never been higher (HLPW, 2018; Leal Filho et
54 al., 2022; UNESCO and UN-Water, 2020) and the increasing world population requires ever more
55 water to satisfy its needs (FAO, 2020). Hence, water scarcity, defined as the imbalance of water
56 demand and supply, and water shortages caused by a sudden lack freshwater are major
57 challenges that humanity must urgently tackle (FAO, 2020; UNCCD and FAO, 2020). Drylands
58 which cover 46.2% of the global land and are inhabited by approximately 3 billion people (IPCC,
59 2019) are particularly susceptible to these threats (Koch and Missimer, 2016; UNCCD, 2017)
60 because of high evaporation losses (Stewart and Peterson, 2015) and climate change impacts
61 (Huang et al., 2017).

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

76 The water yield of sand rivers can be enhanced by constructing small-scale hydraulic retention
77 structures across the riverbed (de Trincheria et al., 2018; Lasage et al., 2008, 2015; Nilsson,
78 1988). Such structures, commonly termed “sand dams”, are impermeable walls which collect the
79 transported sediments during intense rainfall (Neufeld et al., 2021) (Figures 1, 2.a and 2.c). Over
80 the rainy season, sand carried by the river is deposited behind the wall and accumulates until it
81 reaches the top of the dam (sand dam maturation). By storing water in the pores of the sand,
82 evaporation losses are reduced, resulting in a greater quantity of water than similar-sized surface
83 water reservoirs (Lasage et al., 2015). Water quality is also improved because the sand acts as a
84 slow sand filter (Lasage et al., 2015; Quinn et al., 2018). Sand dams are constructed for numerous
85 reasons, such as supporting infrastructure for road crossings and generating sand-filled areas
86 suitable for excavating shallow wells for animal watering (Excellent Development, 2019; Neal,
87 2012). However, the most common purposes are managed aquifer recharge and local water
88 storage (Lasage et al., 2015; Zhang et al., 2020).

89 The performance of sand dams is commonly assessed on both social and environmental benefits.
90 Water is typically accessed in two ways, either via a scoop hole upstream the dam or by an
91 adjacent handpump often dug into the underlying aquifer (Figure 2.b). If the abstraction is
92 carefully managed, the remaining sand-stored water can be beneficial for increasing
93 groundwater levels and growing the surrounding vegetation. However, the trade-off between
94 these differing outcomes needs to be examined when constructing a dam to ensure that the local
95 community's expectations are met (Quinn et al., 2019). The specific topography of the
96 construction sites also needs to be accounted for as very steep and high riverbanks may allow
97 only water withdrawals from the sand river, while shallow banks (flood plains) permit subsurface
98 irrigation opportunities in the nearby areas.

99 The study of sand dam technology has experienced a renewed interest in recent years (Eisma et
100 al., 2021; Eisma and Merwade, 2021, 2020; Ertsen and Ngugi, 2021). Previous literature reviews
101 have summarized current knowledge on the topic, pointing to a range of research gaps that need

102 further scientific attention (Ritchie et al., 2021; Yifru et al., 2021). These reviews mainly focus on
103 the hydrology, water quality (Ritchie et al., 2021) and the planning and implementation of the
104 structures (Yifru et al., 2021), pointing to the need for more long-term watershed-scale analysis
105 and climate change assessments. However, gaps in our understanding of sand dam performance
106 still exist, including the river network- and watershed-scale environmental effects of sand dams,
107 and their interaction with social dynamics. Models predicting the impact of watershed dynamics
108 on sand dams are missing, together with adequate information and analyses on how
109 stakeholders and communities adapt water resources and watershed management after the
110 construction of a sand dam. Furthermore, while all the recent literature on sand dams is seeking
111 more integrated studies on the structures, a clear indication of the future research areas to be
112 prioritized is lacking, together with an identification of suitable and innovative methodologies to
113 address the most relevant research gaps.

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

120 **2. Methodology**

121 Following the analysis of existing scientific literature, the absence of a clear identification of sand
122 dam research priorities and their benefits was highlighted. To address this absence, a
123 collaborative effort was initiated by the Water Harvesting Lab¹ at the University of Florence, with
124 the aim of structuring a discussion on how to classify and analyze existent research gaps and
125 identify possible future research directions. Based on the experience of other collaborative

¹ <https://www.dagri.unifi.it/vp-261-wh-lab.html>

126 commentary papers (Blöschl et al., 2019), the methodology of the work was based on a series of
127 sessions, held within a one-day workshop.

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

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

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

141 The writing process was organized by developing an in-depth analysis of research gaps, with a
142 mixed group of experts involved in writing specific sections of the paper based on their expertise.

143 Expanding from the research gap analysis, the space for new research approaches was defined
144 by focusing on the scientific analysis of sand dams (research frontiers) as a tool of sustainable
145 management and climate change adaptation (figure 3).

146 **3. Results and discussion**

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

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

155 **3.1. Defining and assessing sand dam functionality**

156 Despite the general tendency to think of sand dams as ‘successful or not’, their performance is
157 increasingly recognized to be a spectrum (de Trincheria et al., 2018; Ngugi et al., 2020). Some
158 perform at extremely high levels providing water to their local community throughout the dry
159 season. Others never fully mature or fill with fine particles such as silt or clay rather than sand,
160 and thus provide little to no usable water. As recorded by Ngugi et al. (2020), sand dams exist at
161 nearly every interval between these two extremes. This recent acknowledgment of variable sand
162 dam performance has prompted examination of sand dam functioning (Eisma and Merwade,
163 2020; Neufeld et al., 2021; Ngugi et al., 2020; Quinn et al., 2019). However, the question remains
164 — how should sand dam functioning be defined? Answering this question can guide the selection
165 of appropriate indicators to assess the performance of sand dams in a structured way.

166 We propose that the functioning of sand dams should be assessed relative to their initial
167 purpose, as defined by the communities in which they are built and the organization supporting
168 construction (see Table 1). Three overarching purposes have been identified for sand dams: (1)
169 groundwater recharge (without direct groundwater exploitation by the community near the
170 sand dam – e.g. scoop holes in the riverbed), (2) community water use, and (3) ecological
171 restoration. For sand dams built for groundwater recharge, functioning should be assessed based
172 on the magnitude of water table rise, including consideration of the spatial extent and duration
173 of impact. Other related factors deserving consideration include short and long-term impacts of
174 the raised water table and the local and regional importance of the recharged aquifer. When

175 sand dams are built to provide a water resource to a community, functioning should be assessed
176 based on the number of households served, the duration of support and water quality
177 improvement. This will be impacted by a variety of additional factors including, but not limited
178 to, water use (agricultural, domestic, etc.), other nearby water sources, and local rainfall
179 patterns. Lastly, sand dams constructed for ecological restoration should be assessed based on
180 the increase in local biodiversity. Water has one of the strongest impacts on abundance and
181 movement of wildlife (Naidoo et al., 2020) and water resources in drylands have increased
182 wildlife visits during the dry season (Lundgren et al., 2021). Dryland water resources also support
183 increased germination of local flora (Lundgren et al., 2021), further supporting the idea that
184 biodiversity is a strong indicator of sand dam functioning. Such indicators can either be used to
185 assess the functionality of a single sand dam, or a group of sand dams built in series. In this latter
186 case, the application of the criteria in Table 1 to each of the sand dams in the series can reveal if
187 one of these is performing worse than the others due to upstream-downstream dynamics,
188 poorer local conditions, and/or design and construction inconsistencies.

189 **3.2 Watershed-scale processes – hydrology, sedimentation, and siltation**

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

196 So far, only one peer-reviewed study has been published that uses watershed-scale hydrological
197 modelling to support best practices for sand dam siting or construction, where Eisma et al. (2021)
198 used an integrated hydraulic and hydrologic model of a watershed with three cascading sand
199 dams to examine how land cover, soil texture, and climate factors impacted sand dam

200 performance metrics. This first attempt at applying hydrologic modelling to sand dam siting
201 found that sand dams are better suited in watersheds that are cultivated (in the absence of
202 erosion), sandy, and with a bimodal rainfall pattern. However, in the presence of soil erosion
203 processes in cultivated lands can result in soil loss, causing siltation.

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

208 Sediment dynamics at the watershed scale are even more important for assessing the correct
209 siting of sand dams since the time needed for creating the upstream sand reservoir and the
210 sediment composition determine when and how the sand dam will be effective. In this sense,
211 however, few studies have been carried out since the classical work of Wipplinger (1958). Baurne
212 (1984), Ertsen et al. (2006), Gijsbertsen (2007), de Trinchieria et al. (2015, 2016, 2018), Viducich
213 (2015), Quinn et al. (2019) and Neufeld et al. (2021) have worked on the relationship between
214 sedimentation and the performance of sand dams. Concerns have been raised around dam
215 structures' ability to collect coarser particles, with siltation (accumulation of clay and smaller
216 particles) being observed at numerous sites (de Trinchieria et al., 2018). Methods for minimizing
217 siltation, before project completion, exist, such as terracing surrounding land and constructing
218 the dam across numerous wet seasons (Tiffen et al., 1994); however, it is unclear to what degree
219 these practices are implemented. In addition, current site selection methods, such as examining
220 whether coarse sand is present in the riverbed may be misleading as land use and land cover can
221 change, resulting in erosion and thus increasing the silt present in the ephemeral rivers (Nissen-
222 Petersen, 2011). Few studies have been completed to assess the sediment of existing sand dams.
223 For example, Neufeld et al. (2021) examined the core samples from 97 dams across southern
224 Kenya; they found that although clay and silt were present across all sites, most particles were
225 sandy. However, they estimated that siltation reduced water storage up to 25%, potentially

226 reducing yield from the sand dams by tens of thousands of liters per year. Watershed hydro-
227 sedimentological modelling and erosion analyses, namely the use of watershed scale model to
228 estimate water flows, and erosion-led sediment inputs at a sand dam point, are potential
229 approaches for closing the research gap related to sedimentation and siltation. However, so far,
230 no studies have estimated the time needed for a sand dam to reach maturity based on the
231 watershed characteristics.

232 *3.2.1 Site suitability analyses*

233 Several studies have focused on locating and ranking potential sites for sand dams and other
234 water harvesting structures using spatial decision support systems, based on both physical (e.g.
235 type of soil, land cover, slope) and socio-economic parameters (e.g. distance to settlements,
236 cultivated areas, etc.). These approaches have the advantage of being inexpensive and relatively
237 easy and fast to apply. In their research, Ngugi et al. (2020) used overlay analysis to evaluate
238 existing siting criteria with attributes of sand dams that successfully retained water during the
239 dry period for 116 dams in Kitui County, Kenya, finding consistent patterns for rainfall amount,
240 water indicating vegetation, percentage of clay in soils, stream order and agro-ecological zone;
241 while Forzieri et al. (2008), used a multi-attribute decision method and classification approach
242 to identify coarse geomorphic and hydrological indicators for dam sites in Kidal, Mali. Outside of
243 the peer reviewed literature, organizations have used overlay analysis and weighted criteria to
244 shortlist sites for in-situ survey, such as Excellent Development in Eswatini (Ryan, C., pers comm,
245 2021), Dabane Trust in Zimbabwe (Ngwenya, N., pers comm, 2021), and the World Bank in
246 Somalia and Angola (Limonos, N., pers comm, 2021). More examples are likely to have occurred
247 but have not been documented or shared widely.

248 Despite the findings from these studies, considerable uncertainty remains on the most
249 appropriate criteria for large-scale studies on sand dam siting. Like other river basin-scale
250 models, the main problem for the application of these techniques is the scarcity of input data in

251 remote arid and semi-arid environments, which makes certain simplifications and assumptions
252 necessary. Many assumptions that must be used produce a more conservative approximation of
253 water resource and sediment availability (Love et al., 2011). Another possible development in
254 sand dam siting studies is related to the adoption of specific siting algorithms for different sand
255 dams uses. For instance, while in most cases, sites with a shallow bedrock depth and stony banks
256 present the best siting options, different criteria may be adopted if the goal of sand dam
257 implementation is recharging the riverine and/or the riparian aquifer (Eisma and Merwade,
258 2021).

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

264 **3.3 Social aspects of sand dam research**

265 *3.3.1 Sand dams' exploitation*

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

271 Sand is an important construction material, and sand dams are constructed in sandy riverbeds
272 that can source sand for the construction industry. The practice of selling sand from the riverbed
273 may either decrease water storage capacity or may disincentivize the construction of sand dams
274 in downstream locations (Leal Filho et al., 2021). Further, while sand dams are meant to be a
275 community resource, this is not always well-understood by communities, which may provide an

276 opportunity for a small local subset to seize control of the sand dam for personal use or to sell
277 the water. For example, Hut et al. (2008) noted the use of a diesel pump by some members of
278 the community to extract excessive amounts of water from the sand dam, receiving significantly
279 more benefits at the expense of the larger community. While pumps improve access to the water
280 stored in sand dams, their use for water abstraction must be equitably managed.

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

291 *3.3.2 Community involvement: maintenance and participatory siting*

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

302 communities do not perceive the failure of the sand dam as a loss to their environment,
303 economic wellbeing, and health.

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

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

327 *communities' needs and expectations to avoid conflicts, iii) donor conditions and political and*
328 *administrative leaders' interference and effect on dam siting and functionality.*

329 **3.4 Assessing sand dam performances**

330 Monitoring of water balance, water quality and the environmental effects of sand dams is
331 sporadic, limited to individual dams and case study sites, and only for a few years after
332 construction (Eisma and Merwade, 2020; Quinn et al., 2019). Overall, the main objective of the
333 structures is to enhance water availability from sand rivers, improving communities' socio-
334 economic conditions and livelihoods especially in the dry season and during periods of extreme
335 drought (Lasage et al., 2015). Households tend to move towards higher water consuming
336 activities because of increased water availability. In areas with sand dams, average water
337 consumption per household was about 440 l/day compared to 110 l/day in areas without sand
338 dams (Lasage et al., 2008). This effect is an important factor when considering upscaling sand
339 dams to larger areas. For example, Aerts et al. (2007) showed that in an area with a projected
340 500 to 1500 sand dams, water storage as a percentage of the total annual available water would
341 increase from 3 to 20% under future climate change. Lasage et al. (2015) confirmed such an
342 effect in the dry months in Ethiopia (April and September), and low flow occurrences (Smakhtin
343 et al., 2006) would rise from 18% to, respectively, 23% and 27%. More research is thus needed
344 to assess the potential limits of upscaling of sand dams, and to avoid reduced runoff downstream
345 in the dry season, possibly considering watershed-scale hydrological and socio-economic
346 dynamics (e.g. Bouma et al., 2011).

347 Despite the evident increase in production, a holistic approach to performance assessment is
348 needed, because other recurrent challenges of smallholder farmers, such as low soil fertility or
349 market and credit access can still represent a barrier for livelihoods' improvement (Duker et al.,
350 2020). Irrigation efficiency and water productivity are typically low in sand dam irrigation
351 schemes (Villani et al., 2018), even though it is not clear if improving efficiency would lead to

352 “real” water savings (van Opstal et al., 2021), since a share of the water applied returns to the
353 sand dam aquifer. Nevertheless, evaporation is very high; hence, improved irrigation systems are
354 needed.

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

364 **3.5 Future Research frontiers and opportunities**

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

370 *3.5.1 Social-ecological system perspective and ecosystem services*

371 The gaps identified across the phases of sand dam implementation present an interdisciplinary
372 challenge. From sand dam siting to the definition of a functioning dam, the socio-economic and
373 biophysical aspects of the project need to be carefully integrated. Addressing these gaps in siloes
374 is neither appropriate nor sufficient, given the complex and intertwined links between the socio-
375 economic and environmental aspects of development programs, that are the primary
376 mechanism by which sand dams are built.

377 A consolidated research approach for understanding the complexity of sustainability-related
378 problems and solutions is represented by social-ecological systems (SES) research (Folke, 2006).
379 SES are systems shaped by the complex interplay between nature, economics, and society, which
380 constitute the core unit of study in sustainability science research (Folke et al., 2016). The SES
381 framework has been used to understand and address agricultural and water sustainability issues
382 from the farm to the global scale (Lescourret et al., 2015; Moraine et al., 2017; Piemontese et
383 al., 2020). Framing sand dams as SES can provide a valuable integrated approach to address
384 multiple research gaps, as identified in this work. A SES framework to sand dams could concretely
385 help provide a more comprehensive assessment of the impacts of sand dams considering both
386 the ecological and the socio-economic indicators, revealing potential trade-offs or enhancing
387 positive mechanisms between the socio-economic and the ecological dimensions that are
388 normally overlooked by narrow disciplinary assessments. For example, Di Baldassarre et al.
389 (2015) show how considering an integrated system of hydrological and socio-economic
390 dimensions can reveal the counterintuitive mechanisms of increasing long-term flood risk,
391 because of the construction of flood-containing dams. The SES framework can also be useful to
392 evaluate positive feedbacks related to the engagement of communities in natural resources
393 management and can similarly be applied to sand dam studies (Nagoli et al., 2017). Another
394 practical assessment is provided by Piemontese et al. (2020), who used SES framing to provide
395 context-specific estimates of the potential impact of water harvesting technologies on food
396 production across regions with different social-ecological conditions.

397 Within the SES framework, ecosystem services can represent a practical tool to quantify the
398 potential impact of sand dams on the environment and on people (MEA, 2005). This tool has
399 been applied to evaluate the multiple benefits of different water harvesting structures, such as
400 small dams (Dile et al., 2016; Mastroilli et al., 2018), highlighting both the effects of a single
401 structure and multiple cascading systems. This latter approach is especially useful for a context
402 with a high density of sand dams (e.g. Kitui County, Kenya). The Ecosystem Services approach

403 simultaneously allows the isolation and valuing of the different direct and indirect benefits of
404 sand dams, including increased water availability for people, livestock and agriculture,
405 groundwater recharge, increased vegetation cover, availability of sand as a construction
406 material. This research appeared to be particularly timely, given the momentum imposed by the
407 UN Decade for Ecosystem Restoration for 2021-30. Barriers in applying both approaches include
408 the availability of detailed input data, which are discussed in other sections of the paper.

409 *3.5.2 Exploiting remote sensing applications for watershed-scale analysis*

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

429 airborne observation surveys and unmanned aerial systems is being explored to increase the
430 spatial resolution of geospatial products in related studies (Futurewater, 2017; Hassan-Esfahani
431 et al., 2017; Manfreda et al., 2018).

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

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

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

466 *3.5.3 Building a global dataset for sand dams*

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

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

501 **4. Conclusions and outlook**

502 Gaps in sand dam research are mainly related to sparse information regarding social dynamics
503 connected to sand dam exploitation, limited knowledge about watershed-scale dynamics related

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

517 **References**

- 518 Aerts, J., Lasage, R., Beets, W., de Moel, H., Mutiso, G., Mutiso, S., de Vries, A., 2007.
519 Robustness of Sand Storage Dams under Climate Change. *Vadose Zo. J.* 6, 572.
520 <https://doi.org/10.2136/vzj2006.0097>
- 521 Altchenko, Y., Villholth, K.G., 2015. Mapping irrigation potential from renewable groundwater
522 in Africa - A quantitative hydrological approach. *Hydrol. Earth Syst. Sci.* 19, 1055–1067.
523 <https://doi.org/10.5194/hess-19-1055-2015>
- 524 Amani, M., Ghorbanian, A., Ahmadi, S.A., Kakooei, M., Moghimi, A., Mirmazloumi, S.M.,
525 Moghaddam, S.H.A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., Brisco, B., 2020.
526 Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A
527 Comprehensive Review. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 13, 5326–5350.
528 <https://doi.org/10.1109/JSTARS.2020.3021052>
- 529 Amjath-Babu, T.S., Krupnik, T.J., Kaechele, H., Aravindakshan, S., Sietz, D., 2016. Transitioning
530 to groundwater irrigated intensified agriculture in Sub-Saharan Africa: An indicator based
531 assessment. *Agric. Water Manag.* 168, 125–135. <https://doi.org/10.1016/j.agwat.2016.01.016>
- 532 Balooni, K., Kalro, A.H., Kamalamma, A.G., 2008. Community initiatives in building and
533 managing temporary check-dams across seasonal streams for water harvesting in South India.
534 *Agric. Water Manag.* 95, 1314–1322.
535 <https://doi.org/https://doi.org/10.1016/j.agwat.2008.06.012>
- 536 Baurne, G., 1984. “Trap-dams”: Artificial Subsurface Storage of Water. *Water Int.* 9, 2–9.
537 <https://doi.org/10.1080/02508068408686043>
- 538 Blöschl, G., Bierkens, M.F.P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., Kirchner, J.W.,
539 McDonnell, J.J., Savenije, H.H.G., Sivapalan, M., Stump, C., Toth, E., Volpi, E., Carr, G., Lupton,
540 C., Salinas, J., Széles, B., Viglione, A., Aksoy, H., Allen, S.T., Amin, A., Andréassian, V., Arheimer,
541 B., Aryal, S.K., Baker, V., Bardsley, E., Barendrecht, M.H., Bartosova, A., Batelaan, O., Berghuijs,
542 W.R., Beven, K., Blume, T., Bogaard, T., Borges de Amorim, P., Böttcher, M.E., Boulet, G., Breinl,
543 K., Brilly, M., Brocca, L., Buytaert, W., Castellarin, A., Castelletti, A., Chen, X., Chen, Yangbo,
544 Chen, Yuanfang, Chiffard, P., Claps, P., Clark, M.P., Collins, A.L., Croke, B., Dathe, A., David, P.C.,
545 de Barros, F.P.J., de Rooij, G., di Baldassarre, G., Driscoll, J.M., Duethmann, D., Dwivedi, R., Eris,
546 E., Farmer, W.H., Feiccabrino, J., Ferguson, G., Ferrari, E., Ferraris, S., Fersch, B., Finger, D.,
547 Foglia, L., Fowler, K., Gartsman, B., Gascoin, S., Gaume, E., Gelfan, A., Geris, J., Gharari, S.,
548 Gleeson, T., Glendell, M., Gonzalez Bevacqua, A., González-Dugo, M.P., Grimaldi, S., Gupta,
549 A.B., Guse, B., Han, D., Hannah, D., Harpold, A., Haun, S., Heal, K., Helfricht, K., Herrnegger, M.,
550 Hipsey, M., Hlaváčiková, H., Hohmann, C., Holko, L., Hopkinson, C., Hrachowitz, M.,
551 Illangasekare, T.H., Inam, A., Innocente, C., Istanbuluoglu, E., Jarihani, B., Kalantari, Z., Kalvans,
552 A., Khanal, S., Khatami, S., Kiesel, J., Kirkby, M., Knoben, W., Kochanek, K., Kohnová, S.,
553 Kolechkina, A., Krause, S., Kreamer, D., Kreibich, H., Kunstmann, H., Lange, H., Liberato, M.L.R.,
554 Lindquist, E., Link, T., Liu, J., Loucks, D.P., Luce, C., Mahé, G., Makarieva, O., Malard, J.,
555 Mashtayeva, S., Maskey, S., Mas-Pla, J., Mavrova-Guirguinova, M., Mazzoleni, M., Mernild, S.,
556 Misstear, B.D., Montanari, A., Müller-Thomy, H., Nabizadeh, A., Nardi, F., Neale, C., Nesterova,

557 N., Nurtaev, B., Odongo, V.O., Panda, S., Pande, S., Pang, Z., Papacharalampous, G., Perrin, C.,
558 Pfister, L., Pimentel, R., Polo, M.J., Post, D., Prieto Sierra, C., Ramos, M.H., Renner, M.,
559 Reynolds, J.E., Ridolfi, E., Rigon, R., Riva, M., Robertson, D.E., Rosso, R., Roy, T., Sá, J.H.M.,
560 Salvadori, G., Sandells, M., Schaefli, B., Schumann, A., Scolobig, A., Seibert, J., Servat, E., Shafiei,
561 M., Sharma, A., Sidibe, M., Sidle, R.C., Skaugen, T., Smith, H., Spiessl, S.M., Stein, L., Steinsland,
562 I., Strasser, U., Su, B., Szolgay, J., Tarboton, D., Tauro, F., Thirel, G., Tian, F., Tong, R., Tussupova,
563 K., Tyrallis, H., Uijlenhoet, R., van Beek, R., van der Ent, R.J., van der Ploeg, M., van Loon, A.F.,
564 van Meerveld, I., van Nooijen, R., van Oel, P.R., Vidal, J.P., von Freyberg, J., Vorogushyn, S.,
565 Wachniew, P., Wade, A.J., Ward, P., Westerberg, I.K., White, C., Wood, E.F., Woods, R., Xu, Z.,
566 Yilmaz, K.K., Zhang, Y., 2019. Twenty-three unsolved problems in hydrology (UPH)—a
567 community perspective. *Hydrological Sciences Journal* 64, 1141–1158.
568 <https://doi.org/10.1080/02626667.2019.1620507>

569 Bouma, J.A., Biggs, T.W., Bouwer, L.M., 2011. The downstream externalities of harvesting
570 rainwater in semi-arid watersheds: An Indian case study. *Agric. Water Manag.* 98, 1162–1170.
571 <https://doi.org/https://doi.org/10.1016/j.agwat.2011.02.010>

572 Castelli, G., Bresci, E., 2019. Assessment of water harvesting impacts on water conservation by
573 integrating Landsat 7 and CHIRPS datasets in Google Earth Engine platform. *Rend. Online Soc.*
574 *Geol. Ital.* 48, 47–53. <https://doi.org/10.3301/ROL.2019.37>

575 Castelli, G., Oliveira, L.A.A., Abdelli, F., Dhaou, H., Bresci, E., Ouessar, M., 2019. Effect of
576 traditional check dams (jessour) on soil and olive trees water status in Tunisia. *Sci. Total*
577 *Environ.* 690, 226–236. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.06.514>

578 Cruickshank, A., Grover, V.I., 2012. These are Our Water Pipes—Sand Dams, Women and
579 Donkeys: Dealing with Water Scarcity in Kenya’s Arid and Semi-Arid Lands, in: Leal Filho, W.
580 (Ed.), *Climate Change and the Sustainable Use of Water Resources*, Springer, Berlin pp. 701–
581 726. https://doi.org/10.1007/978-3-642-22266-5_42

582 de Trincheria, J., Leal Filho, W., Otterpohl, R., 2018. Towards a universal optimization of the
583 performance of sand storage dams in arid and semi-arid areas by systematically minimizing
584 vulnerability to siltation: A case study in Makueni, Kenya. *Int. J. Sediment Res.* 33, 221–233.
585 <https://doi.org/https://doi.org/10.1016/j.ijsrc.2018.05.002>

586 de Trincheria, J., Nissen-Petersen, E., Leal Filho, W., Otterphol, R., 2015. Factors affecting the
587 performance and cost-efficiency of sand storage dams in south-eastern Kenya, in: *Proceedings*
588 *of the 36th IAHR World Congress*, Hague, The Netherlands.

589 de Trincheria, J., Wibbing, J., Leal Filho, W., Otterpohl, R., 2016. Practical recommendations to
590 prevent, restore and rehabilitate silted-up sand storage dams in arid and semi-arid areas, in: *E-*
591 *proceedings of the 7th RWSN Forum “Water for Everyone”*, Abidjan, Côte d’Ivoire.

592 Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., Blöschl, G., 2015.
593 *Debates-Perspectives on socio-hydrology: Capturing feedbacks between physical and social*
594 *processes.* *Water Resour. Res.* 51, 4770–4781. <https://doi.org/10.1002/2014WR016416>

595 Dile, Y.T., Karlberg, L., Daggupati, P., Srinivasan, R., Wiberg, D., Rockström, J., 2016. Assessing
596 the implications of water harvesting intensification on upstream-downstream ecosystem

597 services: A case study in the Lake Tana basin. *Sci. Total Environ.* 542, 22–35.
598 <https://doi.org/10.1016/j.scitotenv.2015.10.065>

599 Duker, A., Cambaza, C., Saveca, P., Ponguane, S., Mawoyo, T.A., Hulshof, M., Nkomo, L.,
600 Hussey, S., Van den Pol, B., Vuik, R., Stigter, T., van der Zaag, P., 2020. Using nature-based
601 water storage for smallholder irrigated agriculture in African drylands: Lessons from frugal
602 innovation pilots in Mozambique and Zimbabwe. *Environ. Sci. Policy* 107, 1–6.
603 <https://doi.org/10.1016/j.envsci.2020.02.010>

604 Eisma, J.A., Merwade, V., 2021. A data-driven approach to assessing the impact of water
605 harvesting structures on regional water storage in East Africa. *J. Hydroinformatics* 23, 352–367.
606 <https://doi.org/10.2166/hydro.2021.115>

607 Eisma, J.A., Merwade, V., 2020. Investigating the environmental response to water harvesting
608 structures: a field study in Tanzania. *Hydrol. Earth Syst. Sci.* 24, 1891–1906.
609 <https://doi.org/10.5194/hess-24-1891-2020>

610 Eisma, J.A., Saksena, S., Merwade, V., 2021. Assessing the Impact of Land Cover, Soil, and
611 Climate on the Storage Potential of Dryland Sand Dams. *Front. Water* 3:671455.
612 <https://doi.org/10.3389/frwa.2021.671455>

613 Ertsen, M., Hut, R., van de Giesen, N.C., 2006. Understanding hydrological processes around
614 groundwater dams in Kenya. *Geophysical Research Abstracts*, 8, 00942

615 Ertsen, M., Hut, R., 2009. Two waterfalls do not hear each other. Sand-storage dams, science
616 and sustainable development in Kenya. *Phys. Chem. Earth, Parts A/B/C* 34, 14–22.
617 <https://doi.org/10.1016/j.pce.2008.03.009>

618 Ertsen, M.W., Ngugi, K.N., 2021. Ambivalent Assets: The Success of Sand-Storage Dams for
619 Rainwater Harvesting in Kitui County, Kenya. *Front. Water* 3:676167.
620 <https://doi.org/10.3389/frwa.2021.676167>

621 Excellent Development, 2019. Northern Rangelands Sand Dam Programme 2015 – 2019.
622 Excellent Development: London, UK.

623 FAO, 2020. The State of Food and Agriculture 2020. Overcoming water challenges in
624 agriculture. Rome. <https://doi.org/10.4060/cb1447en>

625 Folke, C., 2006. Resilience: The emergence of a perspective for social–ecological systems
626 analyses. *Glob. Environ. Chang.* 16, 253–267.
627 <https://doi.org/https://doi.org/10.1016/j.gloenvcha.2006.04.002>

628 Folke, C., Biggs, R., Norström, A. V, Reyers, B., Rockström, J., 2016. Social-ecological resilience
629 and biosphere-based sustainability science. *Ecol. Soc.* 21. [https://doi.org/10.5751/ES-08748-](https://doi.org/10.5751/ES-08748-210341)
630 210341

631 Forzieri, G., Gardenti, M., Caparrini, F., Castelli, F., 2008. A methodology for the pre-selection of
632 suitable sites for surface and underground small dams in arid areas: A case study in the region
633 of Kidal, Mali. *Phys. Chem. Earth, Parts A/B/C* 33, 74–85.
634 <https://doi.org/https://doi.org/10.1016/j.pce.2007.04.014>

635 Futurewater, 2017. A4Lab deploys FutureWater's drone technique to explore water potential
636 of dry river beds in Mozambique. [https://www.futurewater.eu/2017/05/a4lab-deploys-](https://www.futurewater.eu/2017/05/a4lab-deploys-futurewaters-drone-technique/)
637 [futurewaters-drone-technique/](https://www.futurewater.eu/2017/05/a4lab-deploys-futurewaters-drone-technique/) [Accessed 18th June 2021].

638 Gaffoor, Z., Pietersen, K., Jovanovic, N., Bagula, A., Kanyerere, T., 2020. Big Data Analytics and
639 Its Role to Support Groundwater Management in the Southern African Development
640 Community. *Water* 12(10): 2796. <https://doi.org/10.3390/w12102796>

641 Gijssbertsen, C., 2007. A study to up-scaling of the principle and sediment (transport) processes
642 behind, sand storage dams, Kitui District, Kenya. MSc thesis. Vrije University, Amsterdam

643 Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., Moore, R., 2017. Google Earth
644 Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* 202, 18–27.
645 <https://doi.org/10.1016/j.rse.2017.06.031>

646 Grigg, N.S., 2016. Social Aspects of Water Management, in: *Integrated Water Resource*
647 *Management*. Palgrave Macmillan, London, pp. 319–338. [https://doi.org/10.1057/978-1-137-](https://doi.org/10.1057/978-1-137-57615-6_17)
648 [57615-6_17](https://doi.org/10.1057/978-1-137-57615-6_17)

649 Hartley, P.A., 1997. Sand-storage dams: an alternate method of rural water supply in Namibia.
650 MSc thesis, University of Cape Town.

651 Hassan-Esfahani, L., Ebtehaj, A.M., Torres-Rua, A., McKee, M., 2017. Spatial Scale Gap Filling
652 Using an Unmanned Aerial System: A Statistical Downscaling Method for Applications in
653 Precision Agriculture. *Sensors* 17(9):2106. <https://doi.org/10.3390/s17092106>

654 Hellwig, D.H.R., 1973. Evaporation of water from sand, 4: The influence of the depth of the
655 water-table and the particle size distribution of the sand. *J. Hydrol.* 18, 317–327.
656 [https://doi.org/https://doi.org/10.1016/0022-1694\(73\)90055-3](https://doi.org/https://doi.org/10.1016/0022-1694(73)90055-3)

657 HLPW, 2018. Making every drop count: An agenda for water action. High-Level Panel on Water
658 Outcome Document

659 Hodgson, S., 2016. Exploring the concept of water tenure. *FAO Land and Water Discussion*
660 *Paper* 10

661 Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang, L.,
662 Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., Yan, H., Wang, G., 2017. Dryland
663 climate change: Recent progress and challenges. *Rev. Geophys.* 55, 719–778.
664 <https://doi.org/https://doi.org/10.1002/2016RG000550>

665 Hut, R., Ertsen, M., Joeman, N., Vergeer, N., Winsemius, H., van de Giesen, N., 2008. Effects of
666 sand storage dams on groundwater levels with examples from Kenya. *Phys. Chem. Earth, Parts*
667 *A/B/C* 33, 56–66. <https://doi.org/https://doi.org/10.1016/j.pce.2007.04.006>

668 IPCC, 2019: Summary for Policymakers. In: *Climate Change and Land: an IPCC special report on*
669 *climate change, desertification, land degradation, sustainable land management, food security,*
670 *and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V.
671 Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M.
672 Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E.
673 Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].

674 Koch, M., Missimer, T.M., 2016. Water resources assessment and management in drylands.
675 *Water*, 8(6):239. <https://doi.org/10.3390/w8060239>

676 Lasage, R., Aerts, J., Mutiso, G.-C.M., de Vries, A., 2008. Potential for community based
677 adaptation to droughts: Sand dams in Kitui, Kenya. *Phys. Chem. Earth, Parts A/B/C* 33, 67–73.
678 <https://doi.org/https://doi.org/10.1016/j.pce.2007.04.009>

679 Lasage, R., Aerts, J.C.J.H., Verburg, P.H., Sileshi, A.S., 2015. The role of small scale sand dams in
680 securing water supply under climate change in Ethiopia. *Mitig. Adapt. Strateg. Glob. Chang.* 20,
681 317–339. <https://doi.org/10.1007/s11027-013-9493-8>

682 Leal Filho, W., Hunt, J., Lingos, A., Platje, J., Vieira, L.W., Will, M., Gavriletea, M.D., 2021. The
683 Unsustainable Use of Sand: Reporting on a Global Problem. *Sustain.* 13(6):3356.
684 <https://doi.org/10.3390/su13063356>

685 Leal Filho, W., Totin, E., Franke, J.A., Andrew, S.M., Abubakar, I.R., Azadi, H., Nunn, P.D.,
686 Ouweneel, B., Williams, P.A., Simpson, N.P., 2022. Understanding responses to climate-related
687 water scarcity in Africa. *Sci. Total Environ.* 806, 150420.
688 <https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.150420>

689 Lescourret, F., Magda, D., Richard, G., Adam-Blondon, A.-F., Bardy, M., Baudry, J., Doussan, I.,
690 Dumont, B., Lefèvre, F., Litrico, I., Martin-Clouaire, R., Montuelle, B., Pellerin, S., Plantegenest,
691 M., Tancoigne, E., Thomas, A., Guyomard, H., Soussana, J.-F., 2015. A social–ecological
692 approach to managing multiple agro-ecosystem services. *Curr. Opin. Environ. Sustain.* 14, 68–
693 75. <https://doi.org/https://doi.org/10.1016/j.cosust.2015.04.001>

694 Love, D., van der Zaag, P., Uhlenbrook, S., Owen, R.J.S., 2011. A water balance modelling
695 approach to optimising the use of water resources in ephemeral sand rivers. *River Res. Appl.*
696 27, 908–925. <https://doi.org/https://doi.org/10.1002/rra.1408>

697 Lundgren, E.J., Ramp, D., Stromberg, J.C., Wu, J., Nieto, N.C., Sluk, M., Moeller, K.T., Wallach,
698 A.D., 2021. Equids engineer desert water availability. *Science*, 372(6541), 491–495.
699 <https://doi.org/10.1126/science.abd6775>

700 Manfreda, S., McCabe, M.F., Miller, P.E., Lucas, R., Pajuelo Madrigal, V., Mallinis, G., Ben Dor,
701 E., Helman, D., Estes, L., Ciraolo, G., Müllerová, J., Tauro, F., De Lima, M.I., De Lima, J.L.M.P.,
702 Maltese, A., Frances, F., Caylor, K., Kohv, M., Perks, M., Ruiz-Pérez, G., Su, Z., Vico, G., Toth, B.,
703 2018. On the Use of Unmanned Aerial Systems for Environmental Monitoring. *Remote Sens.*
704 10(4):641. <https://doi.org/10.3390/rs10040641>

705 Mastroilli, M., Rana, G., Verdiani, G., Tedeschi, G., Fumai, A., Russo, G., 2018. Economic
706 Evaluation of Hydrological Ecosystem Services in Mediterranean River Basins Applied to a Case
707 Study in Southern Italy. *Water* 10(3):241. <https://doi.org/10.3390/w10030241>

708 MEA, 2005. Millennium ecosystem assessment - ecosystems and human well-being: synthesis.
709 Island press, Washington, DC

710 Moraine, M., Duru, M., Therond, O., 2017. A social-ecological framework for analyzing and
711 designing integrated crop–livestock systems from farm to territory levels. *Renew. Agric. Food*
712 *Syst.* 32, 43–56. <https://doi.org/DOI: 10.1017/S1742170515000526>

713 Nagoli, J., Chiwona-Karltun, L., 2017. Uncovering human social networks in coping with Lake
714 Chilwa recessions in Malawi. *J. Environ. Manage.* 192, 134–141.
715 <https://doi.org/10.1016/j.jenvman.2016.12.049>

716 Naidoo, R., Brennan, A., Shapiro, A.C., Beytell, P., Aschenborn, O., Du Preez, P., Kilian, J.W.,
717 Stuart-Hill, G., Taylor, R.D., 2020. Mapping and assessing the impact of small-scale ephemeral
718 water sources on wildlife in an African seasonal savannah. *Ecol. Appl.* 30, e02203.
719 <https://doi.org/https://doi.org/10.1002/eap.2203>

720 Neal, I., 2012. The potential of sand dam road crossings. *Dams Reserv.* 22, 129–143.

721 Neufeld, D.G., Muli, J., Muendo, B., Kanyari, J., 2021. Assessment of water presence and use at
722 sand dams in Kenya. *J. Arid Environ.* 188, 104472.
723 <https://doi.org/https://doi.org/10.1016/j.jaridenv.2021.104472>

724 Neumann, K., Stehfest, E., Verburg, P.H., Siebert, S., Müller, C., Veldkamp, T., 2011. Exploring
725 global irrigation patterns: A multilevel modelling approach. *Agric. Syst.* 104, 703–713.
726 <https://doi.org/10.1016/j.agsy.2011.08.004>

727 Ngugi, K.N.K., Gichaba, C.M.M., Kathumo, V.M.V., Ertsen, M.W.M., 2020. Back to the drawing
728 board: assessing siting guidelines for sand dams in Kenya. *Sustain. Water Resour. Manag.* 6, 58.
729 <https://doi.org/10.1007/s40899-020-00417-4>

730 Nilsson, A., 1988. Groundwater dams for small-scale water supply. Intermediate Technology
731 Publications, London.

732 Nissen-Petersen, E., 2011. Sand dams or silt traps? ASAL Consult. Limited. Available http://www.samsamwater.com/library/Sand_dams_or_silt_traps.pdf [Accessed 13th August 2021].

734 Pekel, J.-F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global
735 surface water and its long-term changes. *Nature* 540, 418–422.
736 <https://doi.org/10.1038/nature20584>

737 Piemontese, L., Castelli, G., Fetzer, I., Barron, J., Liniger, H., Harari, N., Bresci, E., Jaramillo, F.,
738 2020. Estimating the global potential of water harvesting from successful case studies. *Glob.*
739 *Environ. Chang.* 63, 102121. <https://doi.org/10.1016/j.gloenvcha.2020.102121>

740 Piemontese, L., Kamugisha, R.N., Tukahirwa, J.M.B., Tengberg, A., Pedde, S., Jaramillo, F., 2021.
741 Barriers to scaling sustainable land and water management in Uganda: a cross-scale archetype
742 approach. *Ecol. Soc.* 26(3):6. <https://doi.org/10.5751/ES-12531-260306>

743 Quilis, R.O., Hoogmoed, M., Ertsen, M., Foppen, J.W., Hut, R., Vries, A. de, 2009. Measuring and
744 modeling hydrological processes of sand-storage dams on different spatial scales. *Phys. Chem.*
745 *Earth, Parts A/B/C* 34, 289–298. <https://doi.org/https://doi.org/10.1016/j.pce.2008.06.057>

746 Quinn, R., Avis, O., Decker, M., Parker, A., Cairncross, S., 2018. An Assessment of the
747 Microbiological Water Quality of Sand Dams in Southeastern Kenya. *Water* 10(6), 708.
748 <https://doi.org/10.3390/w10060708>

749 Quinn, R., Rushton, K., Parker, A., 2019. An examination of the hydrological system of a sand
750 dam during the dry season leading to water balances. *J. Hydrol.* X 4, 100035.
751 <https://doi.org/https://doi.org/10.1016/j.hydroa.2019.100035>

752 Ritchie, H., Eisma, J.A., Parker, A., 2021. Sand Dams as a Potential Solution to Rural Water
753 Security in Drylands: Existing Research and Future Opportunities. *Front. Water* 3:651954.
754 <https://doi.org/10.3389/frwa.2021.651954>

755 Rosa, L., Chiarelli, D.D., Sangiorgio, M., Beltran-Peña, A.A., Rulli, M.C., D'Odorico, P., Fung, I.,
756 2020. Potential for sustainable irrigation expansion in a 3°C warmer climate. *Proc. Natl. Acad.*
757 *Sci. U.S.A.* 117, 29526–29534. <https://doi.org/10.1073/pnas.2017796117>

758 Ryan, C., Elsner, P., 2016. The potential for sand dams to increase the adaptive capacity of East
759 African drylands to climate change. *Reg. Environ. Chang.* 16, 2087–2096.
760 <https://doi.org/10.1007/s10113-016-0938-y>

761 Singh, P.K., Chudasama, H., 2021. Pathways for climate change adaptations in arid and semi-
762 arid regions. *J. Clean. Prod.* 284, 124744.
763 <https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124744>

764 Smakhtin, V.U., Shilpakar, R.L., Hughes, D.A., 2006. Hydrology-based assessment of
765 environmental flows: an example from Nepal. *Hydrol. Sci. J.* 51, 207–222.
766 <https://doi.org/10.1623/hysj.51.2.207>

767 Stewart, B.A., Peterson, G.A., 2015. Managing green water in dryland agriculture. *Agron. J.* 107,
768 1544–1553. <https://doi.org/10.2134/agronj14.0038>

769 Tiffen, M., Mortimore, M., Gichuki, F., 1994. More people, less erosion: Environmental
770 recovery in Kenya. John Wiley & Sons, Chichester, p. 311.

771 UNCCD, 2017. *The Global Land Outlook*, first edition. Bonn, Germany

772 UNCCD, FAO, 2020. *Land Degradation Neutrality for Water Security and Combatting Drought*.
773 Bonn, Germany

774 UNESCO, UN-Water, 2020. *United Nations World Water Development Report 2020: Water and*
775 *Climate Change*, Paris, UNESCO.

776 Van Opstal, J., Droogers, P., Kaune, A., Steduto, P. and Perry, C. 2021. *Guidance on realizing real*
777 *water savings with crop water productivity interventions*. Wageningen, FAO and FutureWater.
778 <https://doi.org/10.4060/cb3844en>

779 Vidulich, J.M.G., 2015. *Spillway Staging and Selective Sediment Deposition in Sand Storage*
780 *Dams*. MSc thesis, Oregon State University, Corvallis, OR, USA.

781 Villani, L., Castelli, G., Yazew, E., Bresci, E., 2018. Water productivity analysis of sand dams
782 irrigation farming in northern Ethiopia. *Journal of Agriculture and Environment for*
783 *International Development*, 112(1), 139–160. <https://doi.org/10.12895/jaeid.20181.726>

784 Walker, D., Smigaj, M., Jovanovic, N., 2019. Ephemeral sand river flow detection using satellite
785 optical remote sensing. *J. Arid Environ.* 168, 17–25.
786 <https://doi.org/https://doi.org/10.1016/j.jaridenv.2019.05.006>

787 Wipplinger, O., 1958. *Storage of Water in Sand*, South West Africa Administration Water Affairs
788 Branch. Windhoek, Namibia

- 789 Xie, H., Perez, N., Anderson, W., Ringler, C., You, L., 2018. Can Sub-Saharan Africa feed itself?
790 The role of irrigation development in the region's drylands for food security. *Water Int.* 43,
791 796–814. <https://doi.org/10.1080/02508060.2018.1516080>
- 792 Yifru, B.A., Kim, M., Lee, J., Kim, I., Chang, S., Chung, I., 2021. Water Storage in Dry Riverbeds of
793 Arid and Semi-Arid Regions: Overview, Challenges, and Prospects of Sand Dam Technology.
794 *Sustainability*, 12(11):5905. <https://doi.org/10.3390/su13115905>
- 795 You, L., Ringler, C., Wood-Sichra, U., Robertson, R., Wood, S., Zhu, T., Nelson, G., Guo, Z., Sun,
796 Y., 2011. What is the irrigation potential for Africa? A combined biophysical and socioeconomic
797 approach. *Food Policy* 36, 770–782. <https://doi.org/10.1016/j.foodpol.2011.09.001>
- 798 Zhang, H., Xu, Y., Kanyerere, T., 2020. A review of the managed aquifer recharge: Historical
799 development, current situation and perspectives. *Phys. Chem. Earth, Parts A/B/C* 118–119,
800 102887. <https://doi.org/https://doi.org/10.1016/j.pce.2020.102887>

Table 1 - Proposed assessment standard for sand dam functionality

Table 1. Proposed assessment standard for sand dam functionality

Purpose	Indicators	Additional considerations
Groundwater recharge ¹	<ul style="list-style-type: none"> • Water table rise and areal extent • Water volume recharged per unit of time 	<ul style="list-style-type: none"> • Cascading bio-geophysical impacts (vegetation, land subsidence, etc.) • Cascading human impacts (agriculture, greenhouse gas emissions, etc.)
Community water resources	<ul style="list-style-type: none"> • Number of households served • Increased duration of water supply • Improved water quality 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Increased biodiversity • Enhanced Normalized Difference Vegetation Index (NDVI) of riverbanks 	<ul style="list-style-type: none"> • Increased availability and use of natural resources.

¹ without direct groundwater exploitation by the community nearby the sand dam

Figure 1 – Scheme of a sand dam. Adapted from Ritchie et al., 2021

Figure 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)

Figure 3 - Paper methodology

Figure 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

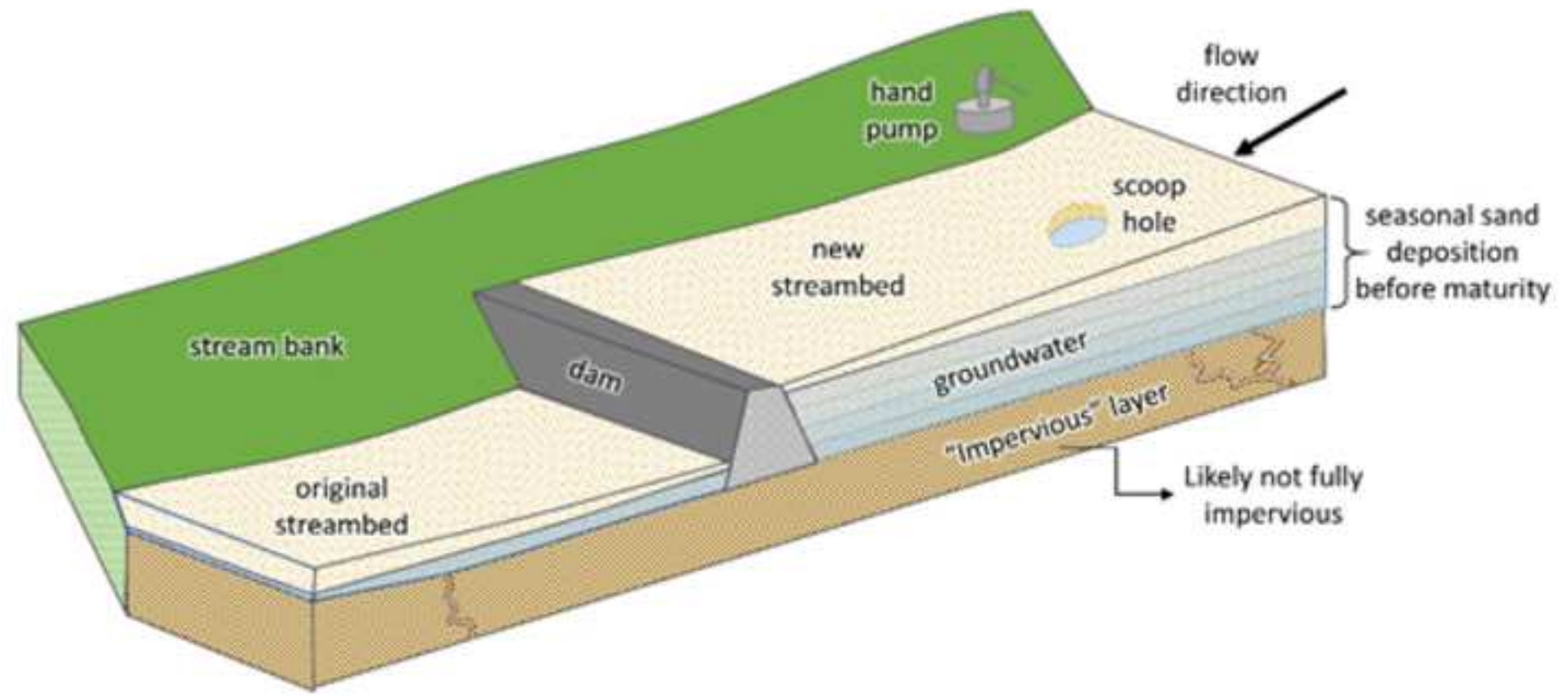
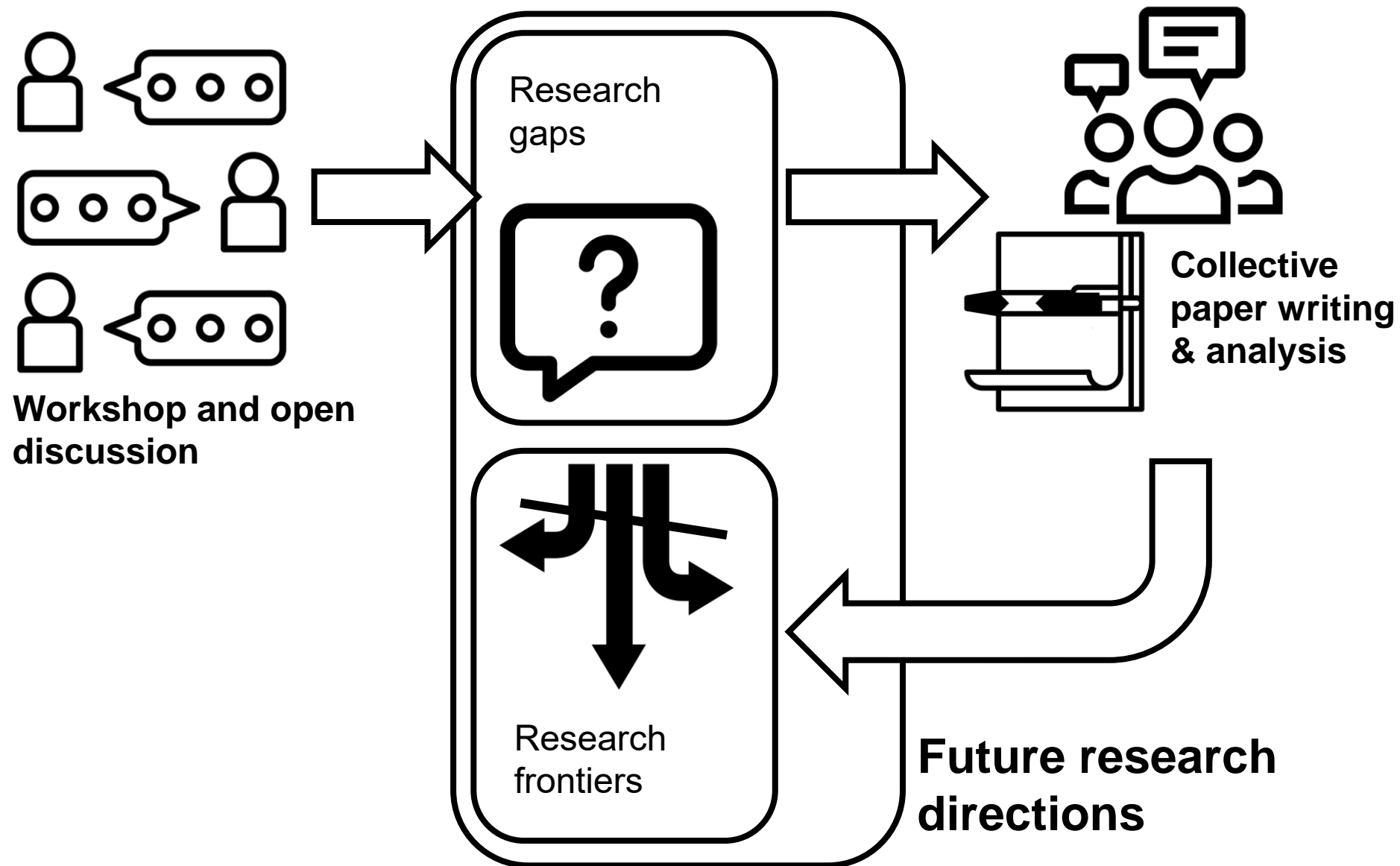




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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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