Chapter

Farm Dams in Southern Africa: Balancing Environmental and Socio-Economic Sustainability

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Abstract

The proliferation and extent of small dams is a significant issue for water resources management. South Africa has an extensive spatial database of farm dams; however, uncertainties remain when estimating the water volume held, although satellite-based techniques offer some means of measurement. This chapter compares various datasets on the occurrence of farm dams in southern Africa and summarises the research on their impacts. Correlations between high-density of small dams and the decline of macroinvertebrate communities, resulting from compromised water quality and low flows, have been established in South Africa. Despite this, the assessment of the cumulative impact of farm dams on riverine ecosystems proves complex due to various uncertainties. The degree of impact varies by dam type, with off-channel dams exhibiting a lower influence on connectivity and sediment dynamics. Efforts to manage and mitigate the effects of small dams is being addressed through a variety of integrated approaches, including: a spatial cost-benefit framework, a model that incorporates different value systems with equitable allocation criteria, and agent-based modelling. The viability of these techniques is dependent upon securing agreement among stakeholders. The chapter concludes with some recommendations for the ways forward.

Keywords: environmental impacts of small dams, cumulative impacts, South Africa, occurrence and extent of small dams, managing and mitigating impacts

1. Introduction

Farm dams have been a part of the agricultural landscape of some parts of southern Africa for a long time. Most of the farm dams were developed and are currently owned and operated by single farming units, although there are some that have been designed to service the water requirements of larger communities of (mostly) subsistence farmers. Small dams play crucial roles in rural communities across many African and Asian countries, particularly during the dry season. Senzanje et al. [1] highlighted their importance in Zimbabwe and advocated for collaboration between communities, NGOs and government to manage and conserve communal small dams. The authors highlighted that these small dams serve multiple purposes including domestic use, irrigation and livestock watering, and brick making, making them invaluable for supporting rural livelihoods and ensuring the long-term sustainability of small-scale farmers. Many of the differences in the occurrence of farm dams across the countries of the southern Africa region are likely related to the evolution of agricultural practices and specifically the differences between those areas dominated by commercial farming and those where communal farming practices dominate. The proliferation of farm dams in parts of South Africa are almost certainly associated with the greater proportion of commercial farms under private ownership relative to other countries. Agriculture in the other countries appears to be mostly based on dryland, non-irrigated farming practices, although a scan of Google Earth imagery suggests that Zambia and parts of Tanzania have several large-scale irrigation schemes that are partly supported by small dams.

In India, Rajendra Singh, an Indian conservationist, has successfully revived the use of *johads*, small earthen percolation dams in semi-arid regions, earning him the prestigious Stockholm Water Prize and the title of 'Waterman of India' (source: https://siwi.org/latest/the-water-man-of-india-receives-stockholm-water-prize/). Similar to small dams in Zimbabwe, these traditional structures in India are communally owned and are designed to capture rainwater and enhance groundwater recharge [2], while also supporting local wildlife. Thus, *johads* allow the villagers to collectively manage their water resources effectively. In southern Africa, small dams are usually associated with irrigation of a variety of crops (including fodder, deciduous and citrus fruits, vines and cereals), stock farming and game reserves [1–3].

Farm dams dominate the landscape of many regions, and Mantel et al. [4] considered them to be convenient surrogates for indicating the level of impact of catchment transformation in rural and peri-urban areas. Farm dams are, however, not high on the research agenda, and therefore there are challenges and uncertainties in quantifying their impacts on riverine ecosystems and their connectivity. This chapter reviews the available information about the occurrence of farm dams in southern Africa, highlights the potential impacts on downstream users and aquatic ecology, and discusses the ways in which these impacts may be assessed and mitigated or managed.

2. The occurrence of farm dams in southern Africa

2.1 Farm dam characterisation

There are different types of farm dams, but most of them fall into the four broad categories illustrated in **Figure 1**. 'No channel' dams are almost always quite small (typically <1 ha) in area and depth and are designed to harvest surface runoff from upslope hillsides. They are mostly used for stock watering and rarely have sufficient storage, and they are too infrequently recharged, for irrigation purposes. The second type is referred to in **Figure 1** as 'On-channel weirs' and represent situations where a river is dammed with a weir and where the storage is confined to the river channel itself. These can vary in size depending upon the gradient and cross-sectional area of the upstream channel. 'On-channel dams' represent those where the dam wall extends beyond the main river channel and where the full supply inundated area is far more than the upstream channel itself. 'Off-channel dams' are typically built close to a river channel which is used to recharge the storage through either pumping, or gravitational flow along a canal connecting the dam with an upstream section of the river. These may also receive some recharge water from upslope surface runoff. The

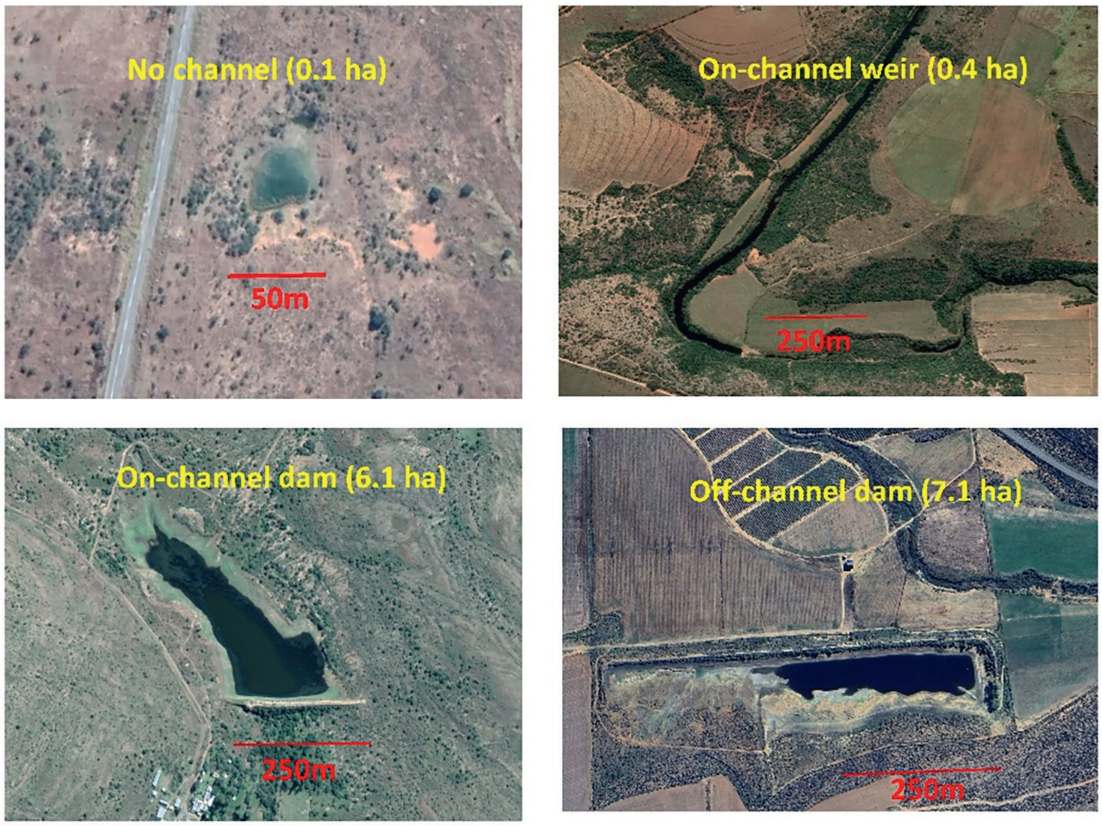

Figure 1.
The main different types of farm dams found in South Africa.

last three can vary in size from quite small to very large, and they are used mostly for irrigation or local domestic water supply.

Sand dams [5, 6] are promoted by the UN Framework Convention on Climate Change (UNFCC) as a sustainable, low maintenance, climate-resilient option for water-scarce areas (http://bitly.ws/Rk7o; accessed 8 Aug 2023), and they are being built in Eswatini through the support of UNDP. These dams are designed to store water in the sediments trapped behind the dam wall, so that they are subject to lower rates of evaporative loss than conventional dams. They are understood to exist in Namibia [7], and possibly other arid parts of the region, but there appears to be no information available on the number and size range.

There are relatively few dams in southern Africa that have been constructed for the purpose of generating hydro-electric power. According to a database compiled by Klunne [8] there are 51 active hydropower stations in South Africa. Most of the larger ones are associated with multi-purpose dams (e.g., the Gariep and Van der Kloof dams on the Orange River) or pump-storage schemes (e.g., the Drakensberg scheme linking the Thukela and Vaal river systems). Most of the smaller schemes are based on run-of-river flows with or without diversion canals from the rivers supplying the water. The situation appears to be similar in other southern Africa countries. While there may be potential for further hydropower development [8, 9], it seems unlikely that this will be associated with many new impoundments that will substantially impact on downstream flow regimes. At the same time, we acknowledge the warning about the global proliferation and impacts of small hydropower plants referred to by others [10–13]. It is interesting to note that the assessment of potential sites summarised in **Figure 6**. and 7 of the Korkovelos et al. [9] study include quite a large number in the very arid Karoo region of South Africa (the west central parts of the country), where the flow regimes are highly ephemeral and very unlikely to justify the costs of even run-of-river hydropower installations.

2.2 Databases and information to assess impacts of farm dams

In order to assess or manage the impact of farm dams in any given catchment, information is required about the upstream catchment area (to assess runoff inputs), surface area (to assess evaporation losses), storage capacity and patterns of abstraction [14]. Surface areas can be estimated quite accurately using satellite imagery and appropriate spatial analysis techniques [15], while upstream catchment areas can, theoretically, be estimated using high resolution digital elevation models and automated catchment definition tools. Patterns of abstraction can normally be estimated on the basis of documented crop requirements where the main water supply purpose is irrigation. However, the actual temporal patterns of abstraction can be highly variable. The main source of uncertainty in most impact assessments of farm dams will typically lie in the estimations of storage capacity [16, 17], in the absence of *in situ* bathymetric surveys, although Rodrigues et al. [18] report on the successful use of remote sensing for storage estimation in Brazil. Similarly, Thompson et al. [19] developed a satellite-based dam volume calculator to provide regular updates of dam storage conditions for South Africa.

McCully [20] estimated that the number of small dams globally was approximately 800,000, using the ratio of large to small dams in the USA (cited in [21]). However, a more recent estimate of the number of low-head dams (with height < 7.6 m) was in excess of 2 million (vs 87,000 large dams) in the USA alone [22]. There are two main local sources of information about the number and location of farm dams in South Africa (including Lesotho and Eswatini), while some farm dams in the region are included as part of the georeferenced global dams and reservoirs (GeoDAR) database [23]. The South African GIS dam coverage and the associated database (AGIS) [24] includes surface area and storage capacity for 3940 'minor dams', but only 152 of these have surface areas of less than 1 ha. The AGIS database is primarily based on information collected from the registered owners of the dams by the Dam Safety Office, and using Google Earth to supplement the database. The HydAreas database, derived from a combination of topographic maps and satellite data, is available from the National Geo-Spatial Information of the South African Department of Agriculture, Land Reform and Rural Development [4]. This database contains surface area information (no capacity data) for 165,728 dams and 67.4% (111,700) of these have surface areas of less than 1 ha. The satellite-derived global GeoDAR database only includes 845 sites for South Africa, many of which are large dams, and is therefore of limited use for understanding the status of farm dam development in South Africa. **Figure 2** illustrates the frequency distributions of surface area for all three databases (excluding those that can be considered as large dams from the GeoDAR database) and storage capacity for the limited sample available in AGIS. The total surface area of the HydAreas small dams is 275,000 ha. Using the AGIS data to calculate the mean depth at full supply capacity (i.e. volume/area), the median depth is some 3 m. Applying a median depth of between 2 m and 4 m (allowing for uncertainty in the actual depths of individual dams) to all the dams in the more complete HydAreas dataset suggests a national total storage capacity of between 5500 × 10^6 m^3 and 11,000 × 10^6 m^3. To put these values into perspective, South Africa's largest dam (Gariep Dam on the Orange River) has an area of 36,000 ha and a capacity of 5674 × 10^6 m^3, while the total area

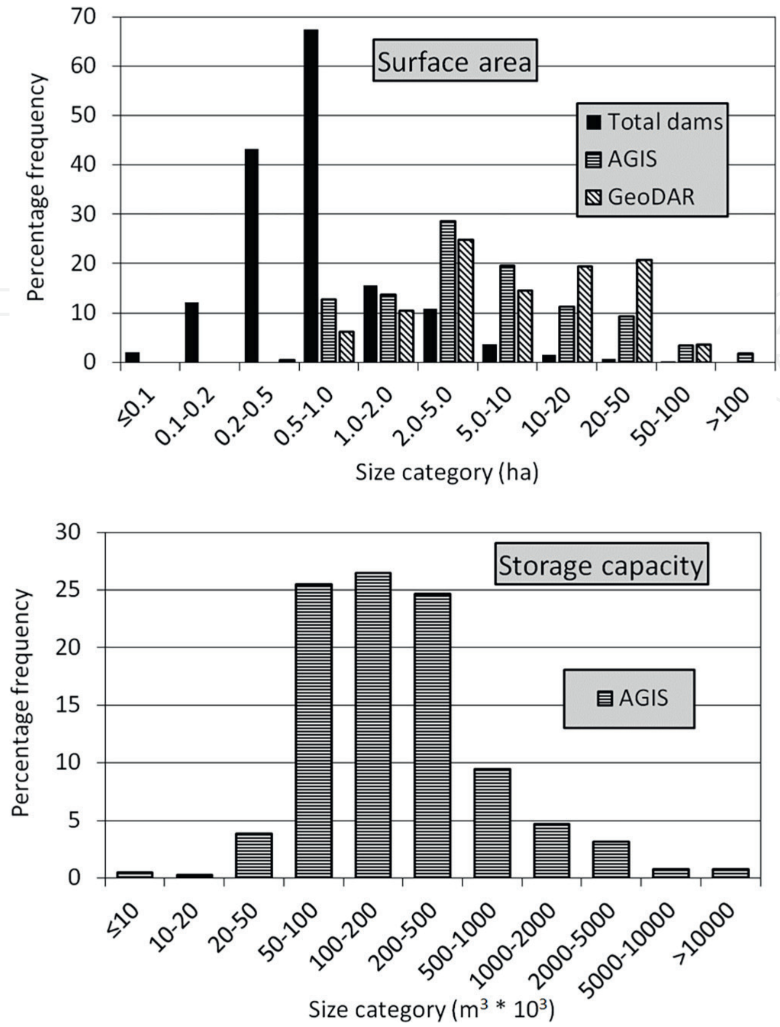

Figure 2.
Frequency distributions of surface area (ha) for the farm dams identified by different data sources (HydAreas, AGIS and GeoDAR) and for capacity ($m^3 \times 10^3$) based on the AGIS data.

and capacity for the 212 major dams listed in the AGIS database are 302,621 ha and 35,541 × 10^6 m^3, respectively. Therefore, while farm dams represent a similar total surface area compared with large dams, they only represent between 16% and 31% of the total storage capacity of large dams.

Inevitably, the impact of farm dams in any given catchment depends on the total number and size, as well as the proportion of the catchment area that lies upstream of the impoundments. Hughes and Mantel [16] referred to three example areas in South Africa where impacts associated with dams used for both irrigation and intensive stock rearing are expected to be quite large. In the headwaters of the Breede River (666 km^2), they reported a total of 376 dams with a combined surface area of 1109 ha, estimated total storage of 48.6 × 10^6 m^3, and with approximately 55% of the total catchment area draining into the dams. A relatively high proportion of the Breede River dams appear to fall into the 'Off-channel' category (**Figure 1**). **Figure 3** illustrates a further extreme example located in one of the headwater tributaries of the Kouga River in the Eastern Cape, South Africa. Within a 45 km^2 part of this catchment (centred on 33.787°S, 23.613°E) there are at least 55 identifiable (using Google Earth imagery) dams ranging in surface area from ~0.1 ha to ~15 ha, all of them being either 'No channel' or 'On-channel' dams. These dams largely support

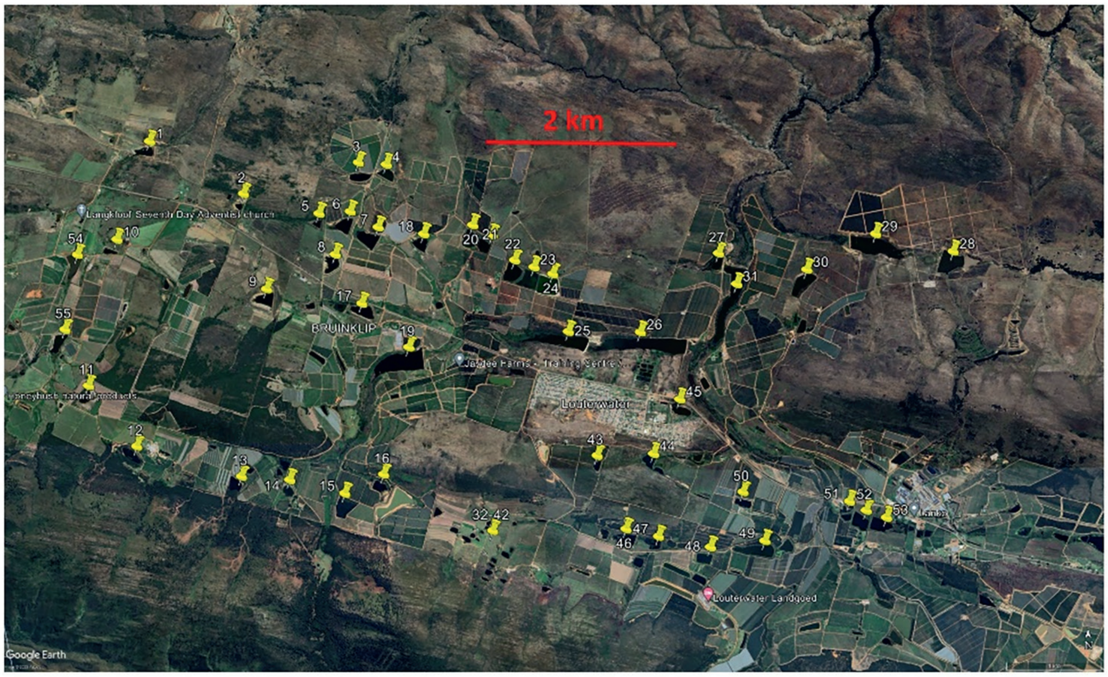

Figure 3.
Google Earth imagery (2023) for a headwater area of the Kouga River, Eastern Cape Province, South Africa, identifying the existing farm dams used for irrigation of deciduous fruit.

large scale commercial deciduous fruit cultivation and many of them appear to have been developed after 1985 and prior to 2004, based on the available historical Google Earth imagery. To illustrate the limitations of some of the available databases, the AGIS database only includes 20 dams for a similar area, while the global GeoDAR database includes even fewer. The flow regimes of the more arid parts of the southern Africa are generally too ephemeral to justify the costs of even small dam development, although Hughes and Mantel [16] included an example from the Hartebeest River in the arid Karoo region of South Africa, where they identified 49 small dams in a 378 km^2 catchment that are used mostly for irrigated fodder crop cultivation.

2.3 Farm dams in southern Africa and database reliability

While there do not seem to be any comparable datasets on farm dams for other countries of southern Africa, a visual assessment (using Google Earth imagery) of the main agricultural areas of Angola, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe suggest that there are fewer areas with the same level of intensive small dam development that are found in several regions of South Africa. Zimbabwe appears to have the next highest level of small dam development and Senzanje et al. [1] suggest that there are some 7000 relatively small dams in the country, although no size statistics are provided to enable comparison with the South African data. **Figure 4** illustrates an area of about 3500 km^2 in the upper reaches of the Hunyani River (a tributary of the Zambezi River) located to the west of Harare and downstream of Lake Manyame. A visual inspection of Google Earth imagery for 2023 suggests that there are at least 84 dams varying in surface area from about 0.5 ha to about 100 ha, but mostly in the range of 5–20 ha. Many of these lie upstream of two major dams in this region (Mazvikadei and Biri dams).

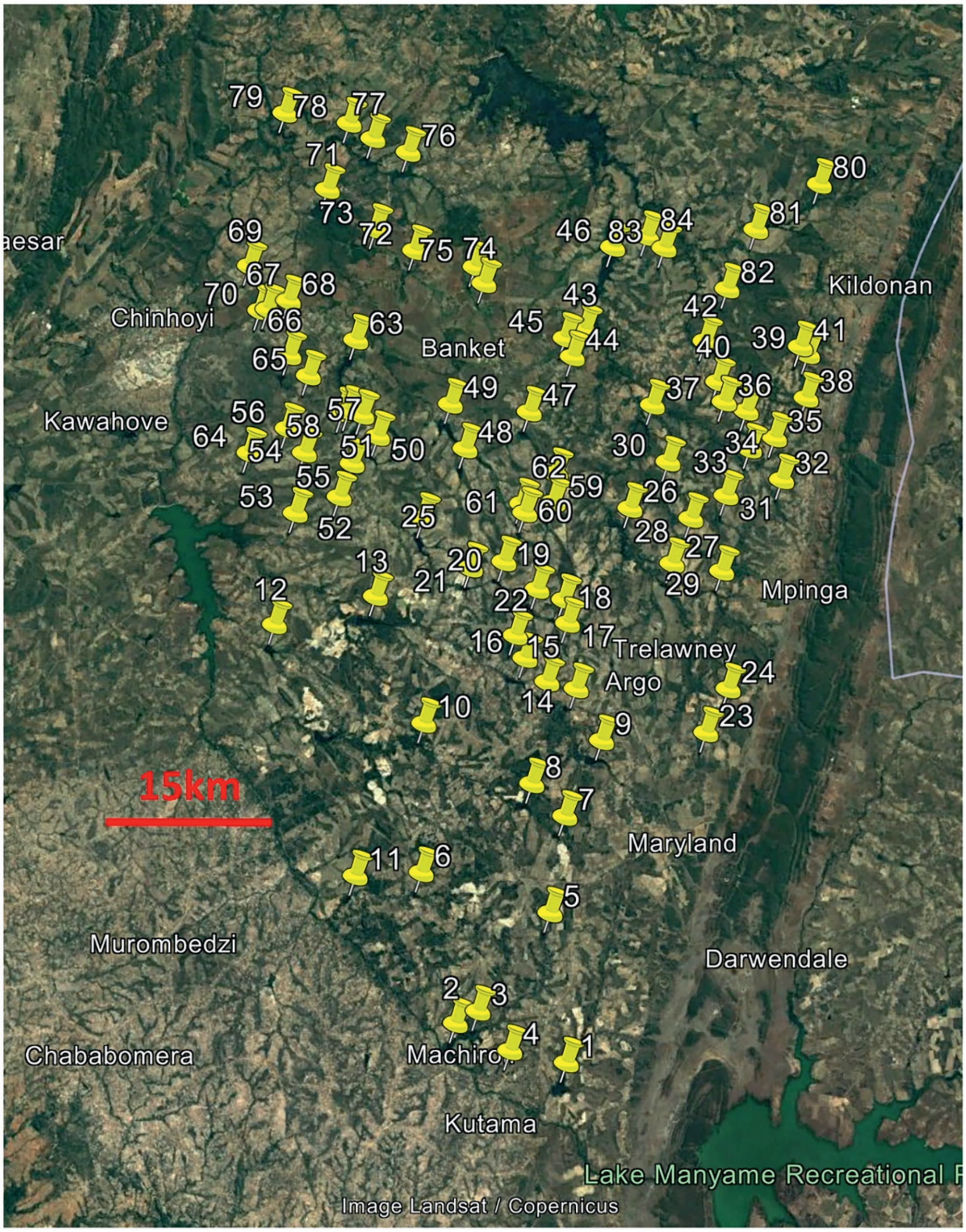

Figure 4.
Google Earth imagery (2023) for a headwater area of the Hunyani River, Mashonaland West, Zimbabwe, identifying the existing farms dams.

Figure 5 illustrates the distribution of the number of farm dams per quaternary catchment area (the standard water management area used in the region) across the whole of South Africa, Lesotho and Eswatini. Using a different metric, that measures the cumulative upstream impact potential, Mantel et al. [4] noted that 52% of the quaternary catchments have a density of small dams that exceeds a threshold where downstream river functionality is likely to be compromised in some way. **Figure 6** shows the spatial distribution of farm dams across South Africa, Lesotho, Eswatini (Swaziland) and Zimbabwe using the GeoDAR dataset based on the level 6 catchment

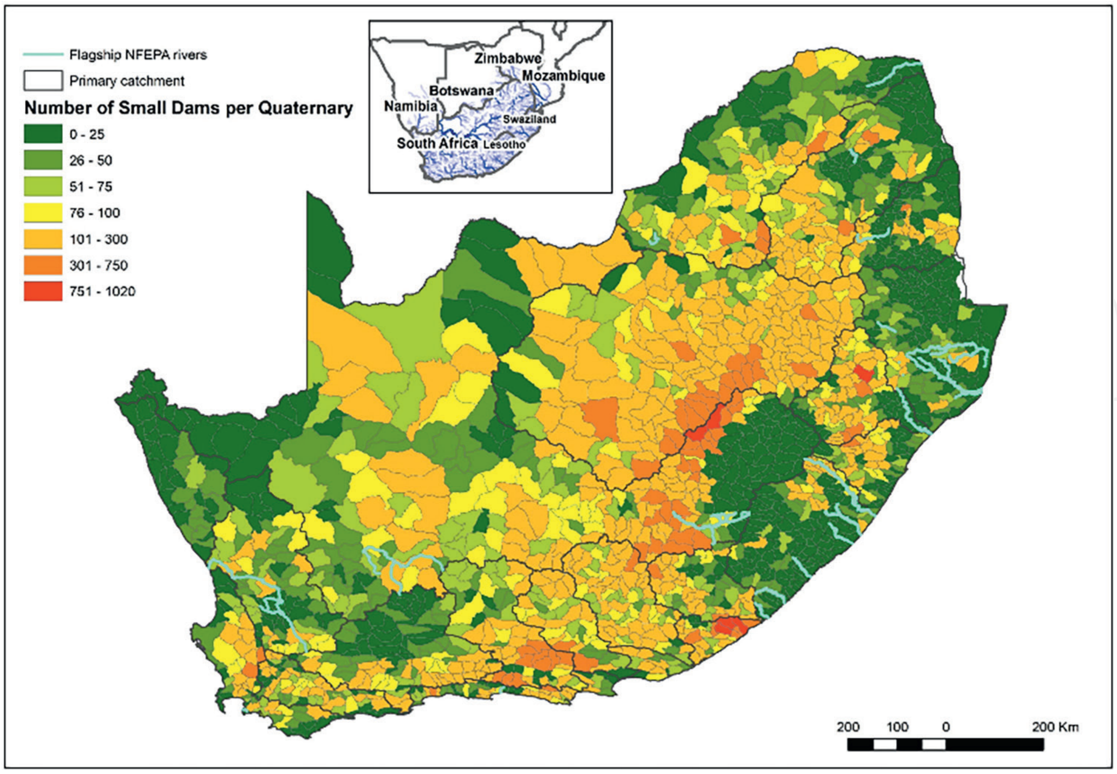

Figure 5.
Number of small dams per quaternary catchment for South Africa, Lesotho and Swaziland (Eswatini) using the HydAreas database. The locations of the 19 flagship, free-flowing rivers, identified by Nel et al. [25] under the National Freshwater Ecosystem Priority Areas (NFEPA) project are shown.

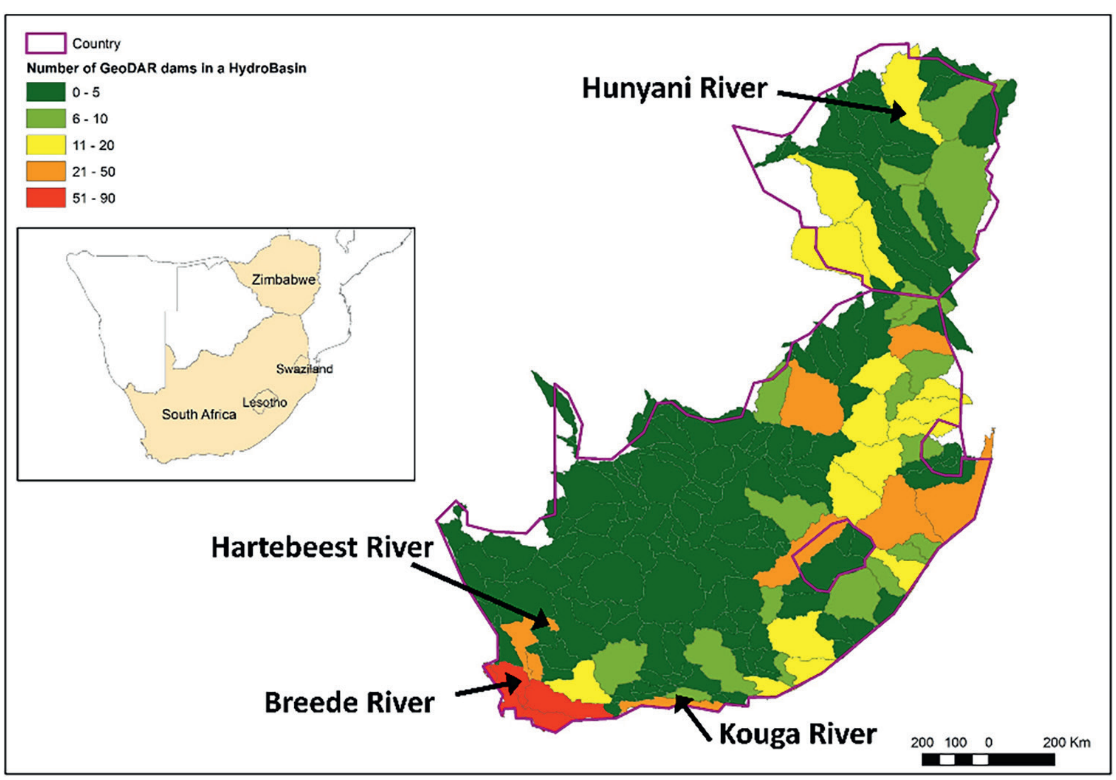

Figure 6.
Number of farms dams for South Africa, Lesotho, Swaziland (Eswatini) and Zimbabwe using catchment areas based on HydroSHEDS and the GeoDAR dams data (the specific catchments referred to in the text and **Figures 3** *and* **4** *are labelled).*

areas from HydroSHEDS [26]. The map suggests that there are similar densities of small dams in Zimbabwe and most of South Africa, but also illustrates that there are some parts of South Africa with substantially higher densities. However, a comparison of **Figure 6** with **Figure 5** and the detailed Google Earth views in **Figures 3** and **4**, indicates that the GeoDAR data cannot be used to reliably assess the occurrence of farm dams in southern Africa.

3. Impacts of farm dams

3.1 Cumulative impacts of farm dams

Individually, small dams have a limited impact on downstream users and environment, such as effects on flow connectivity [27], faunal assemblages [28, 29] and on geomorphological footprints [22]. Inevitably, different dam types (**Figure 1**) will have different individual potential impacts. For example, off-channel dams may have similar impacts on downstream flow reduction (through pumping from the river) as on-channel dams, but they will not impact on flow connectivity or sediment dynamics. However, when the density of small dams surpasses a certain threshold, impairment of downstream ecosystems through cumulative impacts on both water quality (physico-chemistry), macroinvertebrate communities, and reduced water availability during dry periods have been documented in South African rivers [3, 30]. Hughes and Mantel [16] estimated a reduction in mean streamflow of up to 35% in the intensively irrigated headwaters of the Breede River (Western Cape Province, South Africa). The impacts on high flows (exceeded <10% of the time) were expected to be low, but much higher for moderate to low flows (e.g. reductions in the 90% exceeded flow of up to 71%). Within the semi-arid parts of the region natural flow events are infrequent and evaporation losses from the dams are high, suggesting that the impacts on downstream flow regimes are also expected to be high. For the Hartebeest River, referred to earlier, Hughes and Mantel [16] estimated reductions in mean monthly flow of between 30% and 40%, and reductions in both the 10% and 50% exceeded flows of between 50% and 60%. A comparable assessment in Western France [31] reached similar conclusions and suggested that the efficiency of small farms dams in supplying irrigation water and their downstream impacts might decrease due to climate change. Unlike the *johads* in the water-scarce Rajasthan area of India and sand dams in some Africa countries that contribute to shallow groundwater resources ([2], p. 144), there are no documented suggestions that small dams in southern Africa provide similar benefits.

3.2 Farm dam impacts on rivers and beyond

Although the impacts of farm dams on the hydrological regime of a river can only be estimated with quite a high degree of uncertainty [16, 17], there is little doubt that they can be substantial. Mantel et al. [3, 30] used multivariate analysis to study the impacts of small dams on the physico-chemistry and macroinvertebrate biology of rivers in two different climate regions of South Africa (one winter and one summer rainfall region) and the results suggested that impacts were more highly correlated with small dam density than with dam volume. Reduced baseflows due to high densities of small dams were correlated with increased total dissolved salts and shifts to more opportunistic and slow-current taxa in macroinvertebrate communities in

South African rivers [30]. Impacts on downstream discharge reductions and changes in the index of macroinvertebrate health appeared to be greater in the winter rainfall region. However, they acknowledged that attributing impacts to the farm dams themselves is not conclusive as other anthropogenic landscape changes (such as land-use changes) are highly correlated with the density of farm dams. These impacts will vary depending on whether the dams are on- or off-channel.

Apart from the likely impacts on the ecology of the downstream river, farm dams may also impact on downstream water users. For example, the dams in the Kouga River (**Figure 3**) lie upstream of one of the major dams supplying the water requirements of the city of Port Elizabeth to the east. There are, therefore, largely unquantified, conflicts of interest between the supply of water to support a local economy, water to support a nearby large city, and environmental sustainability of the upper reaches of the Kouga River.

The potential *in situ* impacts of the inundated areas of small dams has been the subject of some concern. Rosenberg et al. [21] and St. Louis et al. [32] suggest that there could be as much as three to four times more total reservoir area behind small dams (approximately 1.5×10^6 km^2) in comparison to large ones, although this does not seem to be the case for South Africa where the total surface areas of large and small dams are similar (at approximately 3000 km^2 each). Nevertheless, all reservoirs are a concern from a climate change perspective, as dams are a source of greenhouse gases [32, 33], and thus the Intergovernmental Panel on Climate Change [12] report on climate change and land acknowledges the concerns about the cumulative impacts of small dams, even if they are uncertain.

4. Managing and mitigating impacts

4.1 Various integrated approaches to manage impacts

Figure 7 represents an attempt to summarise the steps in an integrated approach to evaluating water resources management options to achieve sustainable solutions from the multiple perspectives of various socio-economic and environmental concerns. The starting point is a hydrological model that can adequately represent both the natural and modified catchment system, and which includes the simulation of both surface and ground water resources. A number of such models have been applied across many of the countries of southern Africa [34–38]. Given that many parts of the sub-continent are data-scarce regions and given many of the uncertainties in future climate projections, the outputs of these models are frequently in the form of ensembles of plausible, but uncertain outcomes [39, 40]. While the choice of which model to use may depend on a number of factors (including user preference and experience), it is clearly important that the model includes components that simulate all the main anthropogenic impacts, including large dams and smaller farm dams [16, 17]. Many countries of southern Africa have some form of policy and legislation that regulates water use to ensure a defined level of protection for aquatic ecosystems, and methods have been developed to undertake the necessary assessments [41–43] and generate information that is compatible with integrated water resources yield models [44, 45]. The lower part of the diagram represents the main decision-making part of the whole process where various scenarios can be considered in the context of the requirements and attitudes of the full range of stakeholders.

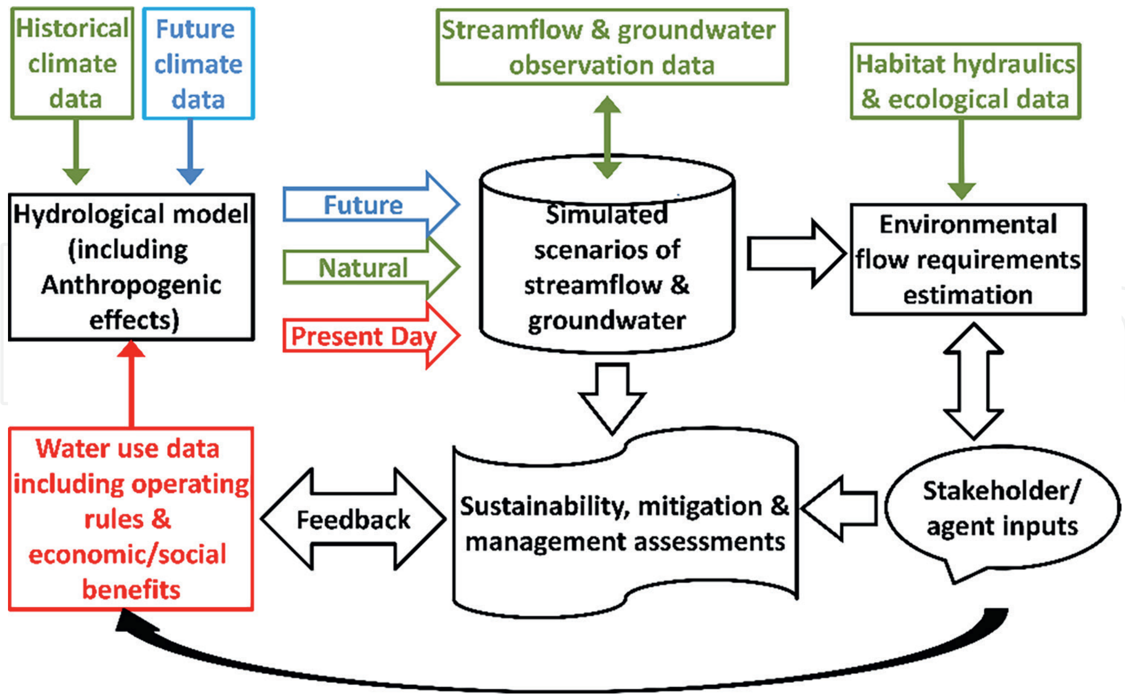

Figure 7.
Simplified summary of the steps in an integrated approach to evaluation of water management options to achieve sustainable solutions.

Hughes and Mallory [46] used a water resources yield model to demonstrate how downstream impacts of dams on river ecology [47] and other water users can be mitigated by managed releases, but this approach is generally only applicable to larger dams that include bottom release capabilities and that are subject to some form of water sharing agreement. Many of the dams constructed in South Africa since the new water act of 1998 are theoretically subject to licencing that includes the need to conform with legislation controlling downstream environmental flow requirements, while the only legislation prior to that date focused on dam safety and was applicable to dams with wall heights over 5 m and capacities exceeding 50×10^3 m^3. However, the majority of the existing farm dams were probably constructed prior to 1998, while others may have been built or extended without approval by the national controlling department (Department of Water and Sanitation; DWS). Even where more recently constructed dams have been designed with the potential to release low flows through a bottom outlet, there is the real possibility that releases are rarely made in the absence of any policing by DWS officials.

Crossman et al. [48] applied a spatial targeting approach within a cost-benefit framework to manage irrigation allocations in Australia. They report multiple benefits that include a reduction in agricultural water use coupled with an increase in the value of agriculture, as well as an increase in the provision of ecosystem services. Pienaar and Hughes [49] suggested an approach that accounts for the integration of different value systems across different water users (e.g. purely economic values related to crop yield, or qualitative values based on perceived benefits of water for social welfare and health), which has recently been extended and tested in a commercial agricultural region of the Western Cape Province of South Africa where there is intense competition for water [50]. Xoxo and co-authors applied an analytic hierarchical process (AHP) to determine equity-based allocation criteria for weighting the needs of various community stakeholders under water deficit conditions.

The combination of the approaches suggested by Pienaar and Hughes [49] and Xoxo et al. [50] contribute to the emerging field of socio-hydrology [51] for decision-making that is participatory, practical and with potential to mitigate conflict, thus ensuring greater chance of success of management plans. Another socio-hydrological approach for getting stakeholder buy-in is agent-based modelling [52] which includes agent behaviours to understand how the system can be managed under different scenarios, and these behaviours can be used to develop an appropriate management plan.

4.2 Challenges and uncertainties in assessing farm dam impacts

Arguably, one of the key issues that affects almost all the components of **Figure 7** is the presence of both aleatory and epistemic uncertainties [49] associated with both data and model limitations. Two key challenges are associated with (a) difficulty in assessing how these dams affect downstream hydrological systems due to uncertainty regarding water volumes and abstraction patterns, as well as a lack of information about dam attributes like wall height, age, and condition; (b) lack of accurate information on the location of small dams in relation to rivers due to the resolution of geographic information system (GIS) datasets. Hughes and Mantel [17] estimated the uncertainties specifically associated with farm dam impacts. While it is important to represent these uncertainties in the whole process [53], not all of the available modelling tools are designed to include uncertainty analysis, and it is not always straightforward to communicate uncertainties to stakeholder groups [54].

Many of the small dams in South Africa would have been constructed prior to the legislation (South African National Water Act, No. 36 of 1998) that accounted for downstream impacts and recognition of the need to maintain aquatic ecosystems and the benefits that they provide. Even now, some 25 years after the legislation was put into effect, it remains difficult to quantify the cumulative effects of farm dams in some parts of the country, partly due to a lack of resources to carry out such assessments together with the large number of catchments that are potentially affected by farm dams. This therefore makes it difficult to undertake assessments of the benefits and dis-benefits of farm dams and identify sustainable management practices. As an example, the South African National Freshwater Ecosystem Priority Areas project (NFEPA) [25] identified spatial priorities that are strategic for conserving water ecosystems for sustainable use of water resources (Second National Water Resources Strategy) [55]. Nineteen flagship, free-flowing rivers, have been identified and Nel et al. [25] recommended that further developments should be limited to ensure that they retain their free-flowing character. If the location of these 19 flagship rivers is compared with the distribution of farms dams (**Figure 5**) it is apparent that some reaches of these rivers overlap with quaternary catchments having more than 100 small dams, raising some concerns about the reality of their designation as 'free-flowing'. Part of the reason for this discrepancy is that the NFEPA only included dams within a 50 m buffer of the main river channel, which effectively ignores the majority of farm dams [4].

5. Conclusions and recommendations

South Africa has a reasonably robust database on the presence of farm dams, far surpassing databases for its neighbouring countries and even global datasets, that often miss a notable portion of small dams. The estimation of water volume held by these dams is, however, considerably uncertain, although certain satellite-based techniques exist for this purpose. Uncertainties also plague our understanding of the operation and the extent of catchment area draining into these dams. These issues are closely linked to whether the dams are situated on- or off-channel.

Quantifying the effects of farm dams on riverine ecosystems presents challenges and uncertainties. These impacts vary based on factors like spatial density and dam type, with off-channel dams having a comparatively lower influence on connectivity and sediment dynamics than on-channel farm dams. Research conducted in South Africa has established correlations between the cumulative impacts of high density of small dams on the deterioration of macroinvertebrate communities. This degradation is connected to degraded water quality and impacted flow regimes, especially during low flow periods. These repercussions may extend to affect downstream water users. Thus, modelling the cumulative impacts of these farm dams and managing water resources at the catchment level are problematic due to a range of uncertainties in our understanding. Notably, the issue of impacted riverine connectivity is not restricted to small dams; it can also be associated with infrastructure such as road-river crossings that include culverts, bridges, fords [56]. Some regions are now focusing more on these infrastructure aspects, incorporating them into proactive planning and strategies for adaptation to climate change [57].

Managing and mitigating the impacts of small dams is being addressed through various integrated approaches, such as the cost-benefit framework used in Australia [48], equity-based allocations using gaming [49, 50] and agent-based modelling [58], both used in South Africa. The feasibility of these various techniques hinge on the considerable effort required to reach agreement among users, and the time required for implementation and the fact that the infrastructure required to manage releases does not exist for older farm dams. External pressures, such as requirements from international markets, may encourage cooperation. For instance, initiatives like the World Wide Fund for Nature's WWF Basket (https://www.wwf.org.uk/wwf-basket) are designed to reduce the environmental impacts of food consumption in the UK. Such initiatives, if successful, can facilitate cooperation among farmers and aid in establishing adherence to environmental flow standards.

We propose two main recommendations for governance actors (government representatives at local, provincial and national levels and non-governmental organisations) involved in water resources management to effectively address uncertainty. Firstly, it is essential for relevant government departments to collate and update data for farm dams, in addition to large dams. Creating open-access databases that store information about the location, volume, and ideally, the operational status of various types of farm dams is highly advisable. These comprehensive databases are vital for accurately quantifying the cumulative effects of different farm dams and other infrastructure, such as road-river crossings. While remote sensing technology is improving and providing more detailed imagery, local databases remain indispensable for validating satellite data and supplementing information that remote sensing cannot capture.

Secondly, there is a need to promote integrated approaches that take into account social, economic, and environmental considerations and constraints when developing robust solutions for water resources planning and management. Embracing socio-hydrological modelling, which facilitates stakeholder engagement and consensus-building around mutually agreed-upon solutions, is particularly important in situations where water resources are contested. While South Africa has made some strides in terms of data availability and integrated modelling, there is still room for greater adoption of these techniques, and other southern African countries (and beyond) need to invest resources into similar datasets along with adoption of proactive management strategies.

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Conflict of interest

The authors declare no conflict of interest.

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References

[1] Senzanje A, Boelee E, Rusere S. Multiple use of water and water productivity of communal small dams in the Limpopo Basin, Zimbabwe. Irrigation & Drainage Systems. 2008;**22**(3-4):225-237

[2] World Commission on Dams. Dams and Development: A New Framework for Decision-Making. VA: Earthscan Publications Ltd; 2000

[3] Mantel SK, Hughes DA, Muller NWJ. Ecological impacts of small dams on South African rivers part 1: Drivers of change—Water quantity and quality. Water SA. 2010;**36**(3):351-360

[4] Mantel SK, Rivers-Moore N, Ramulifho P. Small dams need consideration in riverscape conservation assessments. Aquatic Conservation: Marine and Freshwater Ecosystems. 2017;**27**(4):748-754

[5] Ritchie H, Eisma JA, Parker A. Sand dams as a potential solution to rural water security in drylands: Existing research and future opportunities. Frontiers in Water. 2021;**3**(April):1-18. DOI: 10.3389/frwa.2021.651954

[6] Castelli G, Piemontese L, Quinn R, Aerts J, Elsner P, Ertsen M, et al. Sand dams for sustainable water management: Challenges and future opportunities. Science of the Total Environment. 2022;**838**(December 2021):156126. DOI: 10.1016/j.scitotenv.2022.156126

[7] Hartley PA. Sand-storage dams: An alternate method of rural water supply in Namibia [thesis]. South Africa: University of Cape Town; 1997

[8] Klunne WJ. Small hydropower in southern Africa—An overview of five countries in the region. Journal of Energy in Southern Africa. 2013;**24**(3):14-25. DOI: 10.17159/2413-3051/2013/v24i3a3138

[9] Korkovelos A, Mentis D, Siyal SH, Arderne C, Rogner H, Bazilian M, et al. A geospatial assessment of small-scale hydropower potential in sub-saharan Africa. Energies. 2018;**11**(11):3100-3120. DOI: 10.3390/en11113100

[10] Anderson EP, Freeman MC, Pringle CM. Ecological consequences of hydropower development in Central America: Impacts of small dams and water diversion on neotropical stream fish assemblages. River Research and Applications. 2006;**22**:397-411. DOI: 10.1002/rra.899

[11] Couto TBA, Olden JD. Global proliferation of small hydropower plants – Science and policy. Frontiers in Ecology and the Environment. 2018;**16**(2):91-100. DOI: 10.1002/fee.1746

[12] Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner H-O, Roberts DC, et al, editors. Intergovernmental Panel on Climate Change [IPCC]. Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. 2019. DOI: 10.1017/9781009157988

[13] Jumani S, Rao S, Machado S, Prakash A. Big concerns with small projects: Evaluating the socio-ecological impacts of small hydropower projects in India. Ambio. 2017;**46**(4):500-511. DOI: 10.1007/s13280-016-0855-9

[14] Liebe J, van de Giesen N, Andreini M. Estimation of small reservoir storage capacities in a semi-arid environment. Physics and Chemistry of the Earth. 2005;**30**(6-7):448-454. DOI: 10.1016/j.pce.2005.06.011

[15] Ghansah B, Foster T, Higginbottom TP, Adhikari R, Zwart SJ. Monitoring spatial-temporal variations of surface areas of small reservoirs in Ghana's Upper East Region using Sentinel-2 satellite imagery and machine learning. Physics and Chemistry of the Earth. 2022;**125**:103082. DOI: 10.1016/j.pce.2021.103082

[16] Hughes DA, Mantel SK. Estimating uncertainties in simulations of natural and modified streamflow regimes in South Africa. IAHS-AISH Publication. 2010;**340**(October):358-364

[17] Hughes DA, Mantel SK. Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. Hydrological Sciences Journal. 2010;**55**(4):578-592. DOI: 10.1080/02626667.2010.484903

[18] Rodrigues LN, Sano EE, Steenhuis TS, Passo DP. Estimation of small reservoir storage capacities with remote sensing in the Brazilian Savannah region. Water Resources Management. 2012;**26**:873-882. DOI: 10.1007/s11269-011-9941-8

[19] Thompson M, Hiestermann J, Eady B, Hallowes J. Frankly my dear I give a dam! Or Using satellite observation to determine water resource availability in catchments. In: SANCIAH Conference 2018 Proceedings. Available from: http://sbdvc.ekodata.co.za/Home/About

[20] McCully P. Silenced Rivers: The Ecology and Politics of Large Dams. London, UK: Zed Books; 1996

[21] Rosenberg DM, McCully P, Pringle CM. Global-scale environmental effects of hydrological alterations: Introduction. Bioscience. 2000;**50**(9):746-751. DOI: 10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2

[22] Fencl JS, Mather ME, Costigan KH, Daniels MD. How big of an effect do small dams have? Using geomorphological footprints to quantify spatial impact of low-head dams and identify patterns of across-dam variation. PLoS One. 2015;**10**(11):1-22. DOI: 10.1371/journal.pone.0141210

[23] Wang J, Walter BA, Yao F, Song C, Ding M, Maroof AS, et al. GeoDAR: Georeferenced global dams and reservoirs dataset for bridging attributes and geolocations. Earth System Science Data. 2022;**14**(4):1869-1899. DOI: 10.5194/essd-14-1869-2022

[24] Mallory SJL, Odendaal P. Updating of the South African GIS Dam Coverage and the Associated Database. Water for Africa (Pty) Ltd: South Africa; 2006

[25] Nel J, Maherry A, Petersen C, Roux D, Driver A, Hill L, et al. Technical Report for the National Freshwater Ecosystem Priority Areas project. WRC Report No. 1801/2/11. Pretoria, South Africa: Water Research Commission; 2011

[26] Lehner B, Grill G. Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. Hydrological Processes. 2013;**27**(15):2171-2186. DOI: 10.1002/hyp.9740

[27] Callow JN, Smettem KRJ. The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes. Environmental Modelling & Software. 2009;**24**(8):959-968. DOI: 10.1016/j.envsoft.2009.02.003

[28] Lessard JL, Hayes DB. Effects of elevated water temperature on fish

and macroinvertebrate communities below small dams. River Research and Applications. 2003;**19**(7):721-732. DOI: 10.1002/rra.713

[29] Mbaka JG, Mwaniki MW. A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates. Canadian Journal of Fisheries and Aquatic Sciences. 2015;**23**(3):257-262

[30] Mantel SK, Muller NWJ, Hughes DA. Ecological impacts of small dams on South African rivers part 2: Biotic response - abundance and composition of macroinvertebrate communities. Water SA. 2010;**36**(3):361-370

[31] Habets F, Philippe E, Martin E, David CH, Leseur F. Small farm dams: Impact on river flows and sustainability in a context of climate change. Hydrology and Earth System Sciences. 2014;**18**(10):4207-4222. Available from: https://hess.copernicus.org/articles/18/4207/2014/

[32] St. Louis VL, Kelly CA, Duchemin E, Rudd J, Rosenberg DM. Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. Bioscience. 2000;**50**(9):766-775. DOI: 10.1641/0006-3568(2000)050[0766:RSASOG]2.0.CO;2

[33] Song C, Gardner KH, Klein SJW, Souza SP, Mo W. Cradle-to-grave greenhouse gas emissions from dams in the United States of America. Renewable and Sustainable Energy Reviews. 2018;**90**:945-956. DOI: 10.1016/j.rser.2018.04.014

[34] Akoko G, Le TH, Gomi T, Kato T. A review of SWAT model application in Africa. Water (Switzerland). 2021;**13**(9):1313-1332. Available from: https://www.mdpi.com/2073-4441/13/9/1313

[35] Chawanda CJ, Arnold J, Thiery W, van Griensven A. Mass balance calibration and reservoir representations for large-scale hydrological impact studies using SWAT+. Climatic Change. 2020;**163**(3):1307-1327. DOI: 10.1007/s10584-020-02924-x

[36] Hughes DA. A review of 40 years of hydrological science and practice in Southern Africa using the Pitman rainfall-runoff model. Journal of Hydrology. 2013;**501**:111-124. DOI: 10.1016/j.jhydrol.2013.07.043

[37] Kling H, Stanzel P, Preishuber M. Impact modelling of water resources development and climate scenarios on Zambezi River discharge. Journal of Hydrology: Regional Studies. 2014;**1**:17-43. DOI: 10.1016/j.ejrh.2014.05.002

[38] Winsemius HC, Savenije HHG, Gerrits AMJ, Zapreeva EA, Klees R. Comparison of two model approaches in the Zambezi river basin with regard to model reliability and identifiability. Hydrology and Earth System Sciences. 2006;**10**(3):339-352. DOI: 10.5194/hess-10-339-2006

[39] Borgomeo E, Mortazavi-Naeini M, Hall JW, Guillod BP. Risk, robustness and water resources planning under uncertainty. Earth's Future. 2018;**6**(3):468-487

[40] Kapangaziwiri E, Hughes DA, Wagener T. Incorporating uncertainty in hydrological predictions for gauged and ungauged basins in southern Africa. Hydrological Sciences Journal. 2012;**57**(5):1000-1019. DOI: 10.1080/02626667.2012.690881

[41] Brown C, Campher D, King J. Status and trends in EFlows in southern Africa. Natural Resources

Forum. 2020;**44**(1):66-88. DOI: 10.1111/1477-8947.12190

[42] Hughes DA, Desai AY, Birkhead AL, Louw D. A new approach to rapid, desktop-level, environmental flow assessments for rivers in South Africa. Hydrological Sciences Journal. 2014;**59**(3-4):673-687. DOI: 10.1080/02626667.2013.818220

[43] Joubert AR, Brown CA, King JM, Beuster H, Greyling A. DRIFT: Incorporating an eco-social system network and time series approach into environmental flow assessments. African Journal of Aquatic Science. 2022;**47**(3):338-352. DOI: 10.2989/16085914.2022.2107477

[44] Basson MS, Allen RB, Pegram GGS, van Rooyen JA. Probabilistic Management of Water Resource and Hydropower Systems. Colorado, USA: Water Resources Publications; 1994

[45] Sadeghi B, Borazjani MA, Mardani M, Ziaee S, Mohammadi H. Systemic management of water resources with environmental and climate change considerations. Water Resources Management. 2023;**37**(6-7):2543-2574. DOI: 10.1007/s11269-022-03388-7

[46] Hughes DA, Mallory SJL. The importance of operating rules and assessments of beneficial use in water resource allocation policy and management. Water Policy. 2009;**11**:731-741. DOI: 10.2166/wp.2009.035

[47] King J, Brown C. Environmental flows: Striking the balance between development and resource protection. Ecology and Society. 2006;**11**(2). DOI: 10.5751/ES-01682-110226

[48] Crossman ND, Connor JD, Bryan BA, Summers DM, Ginnivan J. Reconfiguring an irrigation landscape to improve provision of ecosystem services. Ecological Economics. 2010;**69**(5):1031-1042. DOI: 10.1016/j.ecolecon.2009.11.020

[49] Pienaar GW, Hughes DA. Linking hydrological uncertainty with equitable allocation for water resources decision-making. Water Resources Management. 2017;**31**(1):269-282. DOI: 10.1007/s11269-016-1523-3

[50] Xoxo S, Tanner J, Mantel S, Gwapedza D, Paxton B, Hughes D, et al. Equity-based allocation criteria for water deficit periods: A case study in South Africa. In: International Conference on Decision Support System Technology. Switzerland: Springer Nature; 2023. pp. 137-155. DOI: 10.1007/978-3-031-32534-2_11

[51] Younos T, Parece TE, Lee J, Giovannettone J, Armel AJ. Introduction to the special issue "Socio-hydrology: The new paradigm in resilient water management". Hydrology. 2021;**8**(3):2-4. DOI: 10.3390/hydrology8030138

[52] Alam MF, McClain M, Sikka A, Pande S. Understanding human-water feedbacks of interventions in agricultural systems with agent based models: A review. Environmental Research Letters. 2022;**17**(10). DOI: 10.1088/1748-9326/ac91e1

[53] Pappenberger F, Beven KJ. Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water Resources Research. 2006;**42**(5):W05302. DOI: 10.1029/2005WR004820

[54] Pastor AV, Vieira DCS, Soudijn FH, Edelenbosch OY. How uncertainties are tackled in multi-disciplinary science? A review of integrated assessments under global change. Catena. 2020;**186**(February 2019):104305. DOI: 10.1016/j.catena.2019.104305

[55] Department of Water Affairs. National Water Resource Strategy: Water for an Equitable and Sustainable Future. 2nd ed. Pretoria, South Africa; 2013. Available from: https://cer.org.za/wp-content/uploads/2013/07/NWRS2-Final-email-version.pdf

[56] Januchowski-Hartley SR, McIntyre PB, Diebel M, Doran PJ, Infante DM, Joseph C, et al. Restoring aquatic ecosystem connectivity requires expanding inventories of both dams and road crossings. Frontiers in Ecology and the Environment. 2013;**11**(4):211-217. Available from: http://doi.wiley.com/10.1890/120168

[57] Januchowski-Hartley SR, Pawar SK, Yang X, Jorissen M, Bristol R, Mantel S, et al. Supporting proactive planning for climate change adaptation and conservation using an attributed road-river structure dataset. Journal of Environmental Management. 2022;**321**:115959. DOI: 10.1016/j.jenvman.2022.115959

[58] Farolfi S, Müller JP, Bonté B. An iterative construction of multi-agent models to represent water supply and demand dynamics at the catchment level. Environmental Modelling & Software. 2010;**25**(10):1130-1148