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TOPICAL REVIEW

Status of agricultural water management practices in Africa: a review for the prioritisation and operationalisation of the Africa Union's irrigation development and agricultural water management (AU-IDAWM) strategy

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Abstract

Efficient agricultural water management (AWM) practices enhance crop water productivity and promote climate change adaptation and resilience initiatives, particularly in smallholder farming systems. Approximately 90% of sub-Saharan Africa's (SSA) agriculture is rainfed under smallholder farmers who constitute about 60% of the continent's population and depend on agriculture for their livelihoods. While AWM is central to the African agenda, knowledge of AWM is fragmented, making it challenging to operationalize regional initiatives at country levels. Therefore, this study sought to review the status of AWM practices and technologies in Africa and provide guidelines, scenarios, and investment plans to guide the prioritization and operationalization of the African Union's irrigation development and AWM (AU-IDAWM) initiative. The initiative proposes four developmental pathways; 1—improved water control and watershed management in rain-fed farming, 2—farmer-led irrigation, 3—irrigation scheme development and modernization, and 4—unconventional water use for irrigation. The preferred reporting items for systematic reviews and meta-analyses approach guided the systematic literature review. The study indicates that most agricultural production systems are mainly under pathways 1 and 2, which dictate the subsequent AWM practices. Pathway 4 had isolated adoption in North Africa. SSA exhibited overlaps in opportunities for AWM, whereas North Africa had green energy and strong extension services. The challenges were unique to each geopolitical region. Policy-related issues affected North Africa, whilst low investment in AWM dominated West Africa. Poor institutional coordination plagued East Africa, whilst low access to extension services affected Southern Africa. The Central African region was undermined by poor management practices that culminated in soil salinity in the agricultural lands. Targeted and scalable investments across interventions are necessary topotentially improve AWM uptake and subsequent food security in the continent. Also, institutional setups are essential in coordinating efforts towards achieving AWM. Extension services are essential information dissemination platforms for adopting effective climate-smart agriculture.

1. Introduction

An estimated 80% of the global agricultural croplands are rainfed, catering to approximately 60% of global food demands (Ringler *et al* 2022). Erratic rainfall patterns and climate change (CC) threaten agricultural food production by imposing crop failure and consequently yield penalties on farmers. These uncertainties drive concerns of acute food shortages and nutrition security (AU 2020a, Ringler *et al* 2022). Although water consumption by irrigation can exacerbate water shortages, irrigation is a key CC adaptation strategy where water is available (Matthews *et al* 2022). Irrigation development is an ongoing dynamic matrix that involves water control and hydraulic infrastructure designed to regulate flows during conveyance, store water for later use under hydrological variability situations (Borgomeo *et al* 2023) and water governance. Water governance consists of rules, regulations, institutions and procedures involved in agricultural water management (AWM) (Dirwai *et al* 2019b). The dual intention and outcome of irrigation development and water governance are key in devising the adoption of effective AWM practices. AWM is defined as a holistic approach or practice that aims to (1) increase total available water in the plant's root zone, (2) improve soil water holding capacity through mulching practices, (3) promote water harvesting, (4) supply water for irrigation, and (5) employ strategies for improved soil drainage (AU 2020a). Irrigation development and AWM are key drivers for improved water use management and regulation of aggregate water consumption at different farming scales and provide strategic entry points to achieving food and nutrition securities.

Irrigation supports key staples such as maize, wheat, rice and other important dietary crops such as vegetables and fruits, therefore, derived food and nutritional security benefits from functional irrigation systems and appropriate AWM strategies and practices cannot be put at risk. Compared to rainfed agriculture, irrigated agriculture is relatively more productive and generates 40% of global food production on less than one-third (approximately 20%) of the globally harvested area (Ringler *et al* 2022, FAO 2022). Africa has the highest population facing food insecurity due to climate variability (FSIN 2022). Extreme weather events are estimated to affect 23.5 million people in eight African countries (FSIN 2022). Food insecurities drive malnutrition; for example, Africa's prevalence of child stunting is 30.7% (Global Nutrition Report 2022), a figure significantly higher than the global average of 22.0%. CC and climate variability threaten the 500 million smallholder farmers in Africa (You *et al* 2011, Uhlenbrook *et al* 2022); hence to avert continental food and nutrition crises, investment in irrigation development and the subsequent adoption of regionally differentiated and contextual AWM practices for transforming livelihoods is a must-do policy choice for Africa.

Despite possessing an irrigation potential of 24 million hectares, only 6% of Africa's land area is equipped for irrigation (You *et al* 2011, Malabo Montpellier Panel 2018, Uhlenbrook *et al* 2022). This is significantly lower than other regions, such as Asia, which has 34% of the land area equipped for irrigation (You *et al* 2011). Similarly, the share of AWM area realized in Africa is 39% (18.8 million hectares) compared to 68% (212,3 million hectares) in Asia (Ringler 2021). Furthermore, the top five irrigating states in the USA (Nebraska, Arkansas, California, Texas and Idaho) contribute 50.1% (approximately 11.8 million hectares) of the total land for irrigation (USDA 2022). The presented statistics call for significant funding and purposeful, transformative agricultural policies to drive African irrigation development and AWM.

As well as strategically increasing irrigated areas, investments in irrigation development in Africa should target the rehabilitation and revitalization of what is already on the ground (Wiggins and Lankford 2019). Of the total hectarage under irrigation, an estimated 1 million hectares have infrastructure that requires rehabilitation (You 2008). The scale of rehabilitation varies across the countries, with the worst affected countries being Lesotho requiring 100% rehabilitation, followed by Benin at 80% requirement and Sudan requiring 75% rehabilitation (You 2008). South Africa, Zambia, Madagascar and Burkina Faso are some of the few countries requiring minimal irrigation rehabilitation (You 2008). Deliberate government interventions and commitments are key for realizing transformative adaption in agriculture. For example, efforts by the South African government to invest in the revitalization of smallholder irrigation schemes program proved pivotal in ensuring improved water use efficiency and minimizing yield penalties (Denison and Manona 2007). Likewise, the 3-tier irrigation system policy adopted in Zambia is an innovation designed to promote smallholder growth and operation by leveraging an established medium and large-scale farming enterprise (Akayombokwa *et al* 2015).

The investments in irrigation and AWM often favour the existing and established pathways, namely, farmer-led irrigation, and small and large schemes, for commercial farms. These agricultural pathways dominate policy dialogue; while a gap exists in addressing the pathways on wastewater and circular economy use in urban and peri-urban areas as well rainfed agriculture in Africa. African cities are slowly becoming agricultural hubs to meet food demands for the burgeoning urban population, hence, regulating wastewater usage for irrigation facilitates food production means (Zhang and Shen 2019), and subsequently, boost livelihoods through extra income and can potentially ease localised demands freshwater at critical junctures for irrigation (Lankford 2023).

This review sought to explore the development pathways outlined in the Africa Union's irrigation development and AWM (AU-IDAWM) framework and delineate them according to the different geopolitical regions in Africa. Pathway delineation provides a nuanced difference in Africa's food production systems by providing localised and contextual parameters to assess and analyse regional deficits that subsequently influence AWM.

1.1. The irrigation development and AWM framework

An Africa-wide continental response to underperforming irrigation development and AWM is spelt out in the AU-IDAWM (AU 2020a). The AU-IDAWM is adaptable across scales and consists of four developmental pathways catering to responsive agricultural development. The four pathways are:

- Pathway 1: Improved water control and watershed management in rain-fed farming,
- Pathway 2: Farmer-led irrigation development (FLID),
- Pathway 3: Irrigation scheme development and modernization, and
- Pathway 4: Unconventional water use for irrigation.

The four pathways were developed to respond to the variety of farming systems in Africa. For example, pathway 1 targets rain-fed farming which is predominant compared to irrigated agriculture in Africa. Rain-fed farming is mainly practised by smallholders located in rural areas. Pathway 2 addresses FLID issues that have dominated the research space for nearly two decades examining smallholder use of common pool resources, such as water, to irrigate their fields. The FLID setting resembles a typical irrigation scheme with a water user association (WUA) that manages water politics amongst the farmers. Pathway 3 examines modernization versus building new schemes recognising the high establishment costs involved in constructing new schemes. In contrast, pathway 4 emphasizes utilizing waste water for irrigation to reduce fresh water demands (AU 2020b).

Accordingly, this study aimed to review the status, opportunities, and challenges of AWM practices in Africa. The review adopts the pathways as presented by the AU-IDAWM framework. Lastly, the review provides recommendations for operationalizing a regionally differentiated AU-IDAWM framework.

2. Methodology

The review was guided by the preferred reporting items for systematic reviews and meta-analyses (PRISMA) protocols by Page *et al* (2021). The PRISMA approach was guided by the objectives of the study.

2.1. Eligibility criteria

The study utilized the Google Schoilar (for grey literature), Scopus and Web of Science (WoS) search platform. In the WoS platform, the authors searched all editions of the WoS core collection. To narrow the review's focus and provide a comprehensive literature outcome, the literature search was restricted so that the review focused primarily on studies that;

i. highlighted rainwater harvesting and rain-fed crop production,
ii. spoke about different variants of FLID at varying scales,
iii. focused on irrigation scheme revitalization and rehabilitation,
iv. spoke about wastewater or unconventional water use in irrigation,
v. detailed regional and national irrigation policy formulation and evolution,
vi. had an agricultural technology intervention,
vii. outlined investments around national built environment infrastructure, and
viii. assessed empirically derived impact indicators, e.g. yield, household income, and water use efficiency.

A series of search queries (table 1) were used to search for articles in the Scopus database. The first variables on the search string were interchanged between livelihood indicators and farming typology. The subsequent terms were random card search strings related to the above-listed criteria. In addition, filter functions in the Scopus database ('*limit to*' and '*exclude*') and WoS ('*exclude*' and '*refine*') were utilized for prescreening studies not related to agricultural sciences and the related proxies. The articles were further screened to identify context-specific journal articles, reports and conference proceedings.

Table 1. Search query employed in the study.

First row		Second row		Third row
'yield*' **OR** 'food security*' **OR** 'nutrition security*' **OR** 'smallholder*'	**AND**	'Irrigation modernisation*' **OR** 'irrigation typology*' **OR** 'farmer-led irrigation development*' **OR** 'watershed management*' **OR** 'rain-fed*'	AND	'National irrigation policy*' **OR** 'water governance*' **OR** 'ecosystems*' **OR** 'Africa*'

Table 2. The inclusion and exclusion criteria employed in the study.

Inclusion	Exclusion
Articles published in English	Articles from predatory journals as outlined in the updated Beall (2020) list of predatory journals.
Original research in peer-reviewed journals	Articles not published in English
Conference proceedings	Full articles that could not be retrieved
MSc and PhD theses Government Gazettes	Articles with insufficient and irrelevant results, discussion and conclusions
Article profiling smallholder irrigation research globally	
Books and book chapters	

2.2. Inclusion and exclusion criteria

The search criteria emphasized publication year; we considered articles published within the past decade. Also, articles not published in English were not considered. Table 2 presents the comprehensive inclusion and exclusion criteria used in the study.

The review is organized as follows: the next section details the results from the literature search. After that, we discuss the results presented from the Sankey plot linking geopolitical regions and development pathways. The next section discusses the challenges and opportunities in each geopolitical region. We provide evidence from the respective countries to support our discussions on national policy frameworks and IDAWM. Lastly, we provide recommendations for operationalizing the regionally differentiated IDAWM framework.

3. Results and discussions

3.1. Literature search

The disaggregated literature included in this review had $n = 3$ papers from North Africa, whilst East, West and Central Africa had $n = 42$, $n = 21$, and $n = 9$, respectively. Southern Africa data entities were $n = 44$. The literature contributions are summarised in Figure 1 below.

The results are summarised in the PRISMA flow chart below (figure 2).

3.2. AU-IDAWM pathway adoption across the different geopolitical regions of Africa

We developed a Sankey plot linking IDAWM pathways to AWM practices across the five geopolitical regions (figure 3). The Sankey plot was developed in R-Studio. The results exhibited different pathway adoptions and AWM uptakes.

3.2.1. AWM practices by region

Our interpretation of our review is as follows: Africa consists of five geopolitical regions (figure 3). The different regions showed a heterogenous AWM landscape typified mainly by FLID (under irrigation schemes and individual farmers) and a few cases of unconventional wastewater use (pathway 4). Based on our findings, North Africa was characterised by dominant pathways 2 and 3, and to a lesser degree pathways 1 and 4. Irrigation and AWM is essential in North Africa because of the region's arid conditions and water scarcity (Ringler 2021). North Africa utilises the Nile River and other major river systems for irrigation (Dixon *et al* 2001) and hence the probable AWM practice would be the rehabilitation of irrigation schemes to improve conveyance efficiencies. The region irrigates to boost yield and to meet moisture deficits under variable precipitation during winter seasons (Rusu and Simionescu 2016). Regarding the operationalisation of pathway 4, Egypt recorded the highest hectarage (35 500 ha) under unconventional water use, and Libya had the least in North Africa (approx. 2900 ha). North African countries had pronounced unconventional water usage for irrigation, with the bulk of the water coming from wastewater.

Eastern Africa was characterized by the use of hybrid crop varieties and application of soil and water conservation techniques for runoff control planning and, subsequently, rainwater harvesting (Awulachew

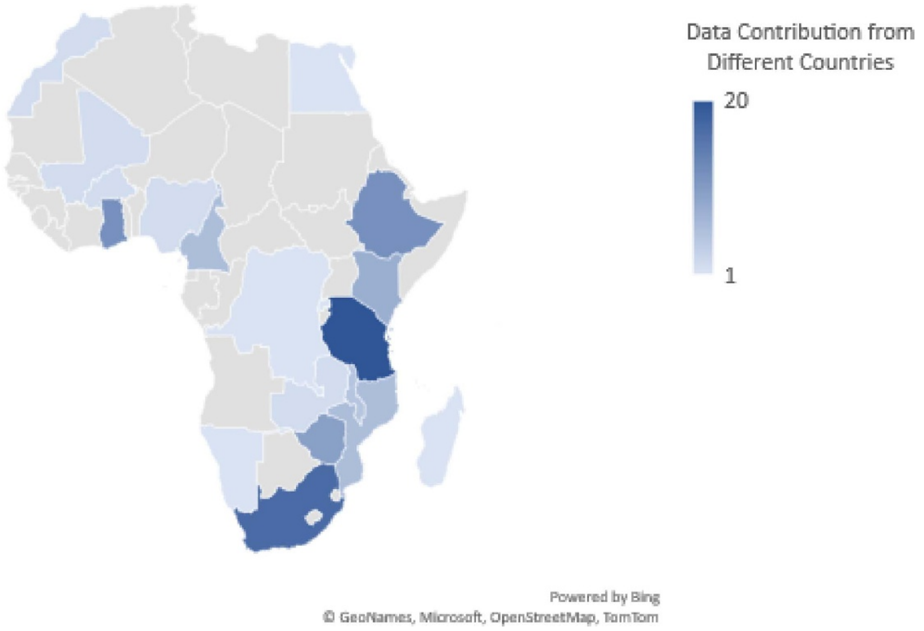

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Figure 1. Spatial distribution of the articles retrieved from the contributing countries. Data contribution means the country where each study was based.

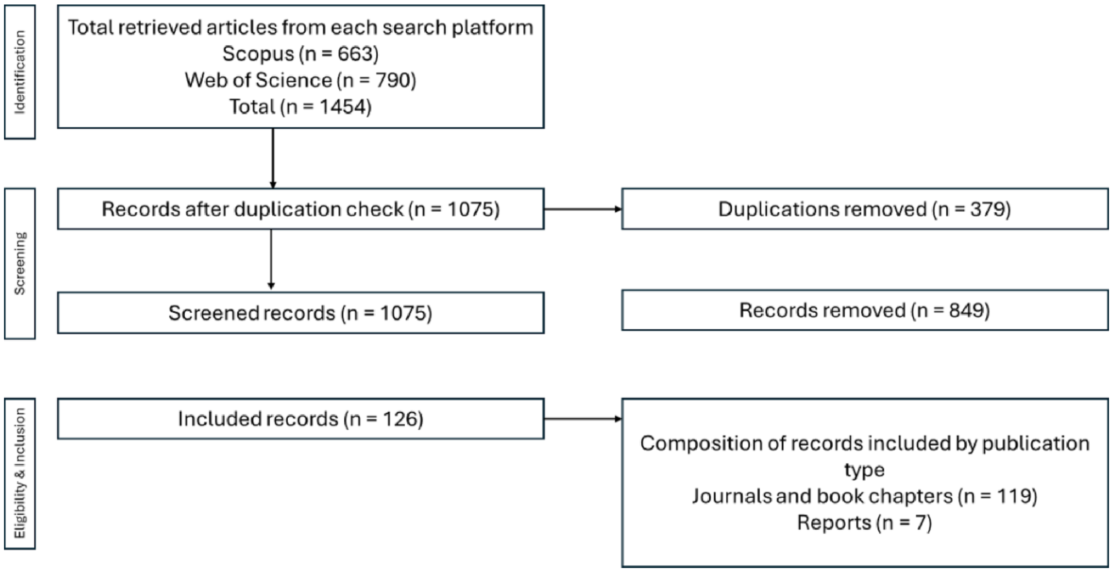

Figure 2. PRISMA flow chart depicting records used for literature synthesis.

and Ayana 2011, Amede 2015, de Bont *et al* 2019), whilst Central Africa had either pathways 1, 2 or a combination of the two pathways, which utilized water harvesting, crop rotations, drip irrigation use, and use of hybrid crop varieties as AWM coping mechanism (Nwajiuba *et al* 2015, Faustino *et al* 2021, Waalewijn 2021).

In West Africa, pathway 2 was dominant, followed by pathway 1 and a combination of pathways 1 and 2. The identified combined adoption of pathway 1 and pathway 2 involved a combination of runoff harvesting, storage and pumping systems during dry spells. Other AWM practices that were found prevalent in West Africa were intercropping permanent soil cover, and minimum tillage.

Southern Africa was mainly characterized by pathway 2, and the dominant AWM practices were mulching, rainwater harvesting, in some cases use of drought tolerant varieties and zero tillage (Nwajiuba *et al* 2015, Thierfelder *et al* 2016a, 2016b, 2017, 2018, Moyo *et al* 2017). Pathway 1 contributed to the southern African dataset, revealing mulching, agroforestry, and intercropping as adaptation strategies for improved AWM to mention a few (Rusinamhodzi

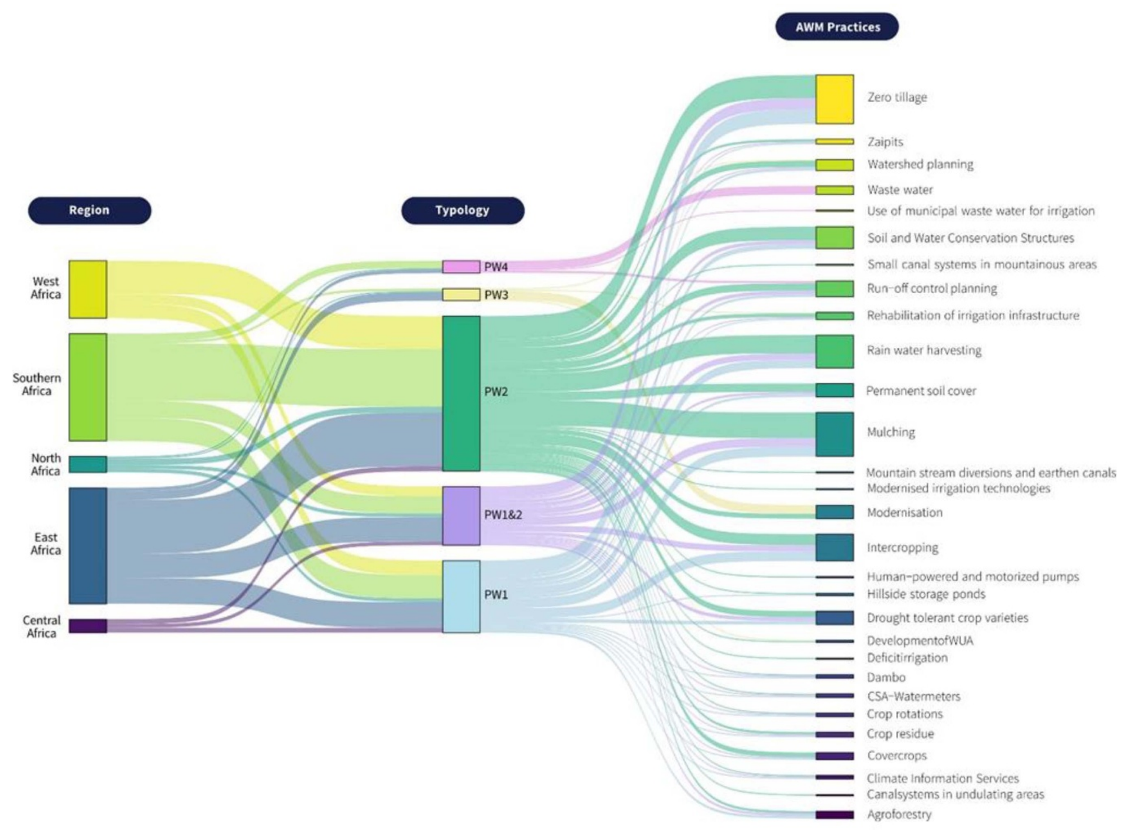

Figure 3. Relationships amongst geopolitical regions, irrigation pathways, and AWM practices. (PW = AU-IDAWM pathway).

et al 2011, Thierfelder *et al* 2015, Strauss *et al* 2021, Van Antwerpen *et al* 2021).

Data on Central Africa was revatively thin ($n = 9$), however, from our analysis, the region was characterised by pathways 1 and 2. The subsequent AWM practices in Cameroon included agroforestry, mulching, utilising climate information for timing planting dates, crop rotations, and water harvesting to mention a few (Chinedum *et al* 2015). In the DRC, some of the AWM strategies included soil and water conservation strategies such as constructing contour bunds, use of early maturing varieties, and organic manure application to improve soil fertility, especially in the subtropical and mountainous southern Kasai and south western Kasai central.

We finish this overview with some additional observations. In our understanding, PW2 is dominant across all geopolitical regions because most farming systems in Africa comprise smallholder farmers. Approximately 90% of agriculture production is rainfed, and smallholder farmers account for 70% of the population (AGRA 2017). Hence, targeted investment is required to improve the status of irrigation and water storage and conveyancing facilities to improve the AWM in the different pathways.

Pathway 4 is the least developed in the continent despite its promising potential to augment and boost food production under the different production pathways (PW 1, 2, and 3) (see figure 4). However, it is worth noting that sub-Saharan Africa (SSA) had non-documented evidence of unconventional water use, hence the operationalisation statistic for pathway 4 could be higher. We opine that both coastal and landlocked countries capitalize on wastewater usage to ease localised freshwater demands. Another potential entry point for coastal countries (e.g. Egypt) is utilizing desalination technology despite the initial high establishment costs of the technology and high energy requirements to desalinate and pump the water uphill from sea level. The two entry points (maximizing wastewater generated in cities and desalination) could potentially facilitate the operationalization of the continent's blue economy strategy.

All the AU-IDAWM pathways are present in North Africa, and FLID is the dominant pathway. Farmers practising FLID engage in different AWM practices ranging from mulching conservation agriculture (CA) to crop rotations. Although the FLID pathway is fraught with challenges, there also exists opportunities to grow the pathways towards sustainability (figure 3). Energy generation for irrigation is a concern (Balasubramanya *et al* 2024) as this is also required to supply power to the rapidly mushrooming urban populace, which in turn competes for limited water resources. Increased competition for freshwater resources has a negative trickle-down

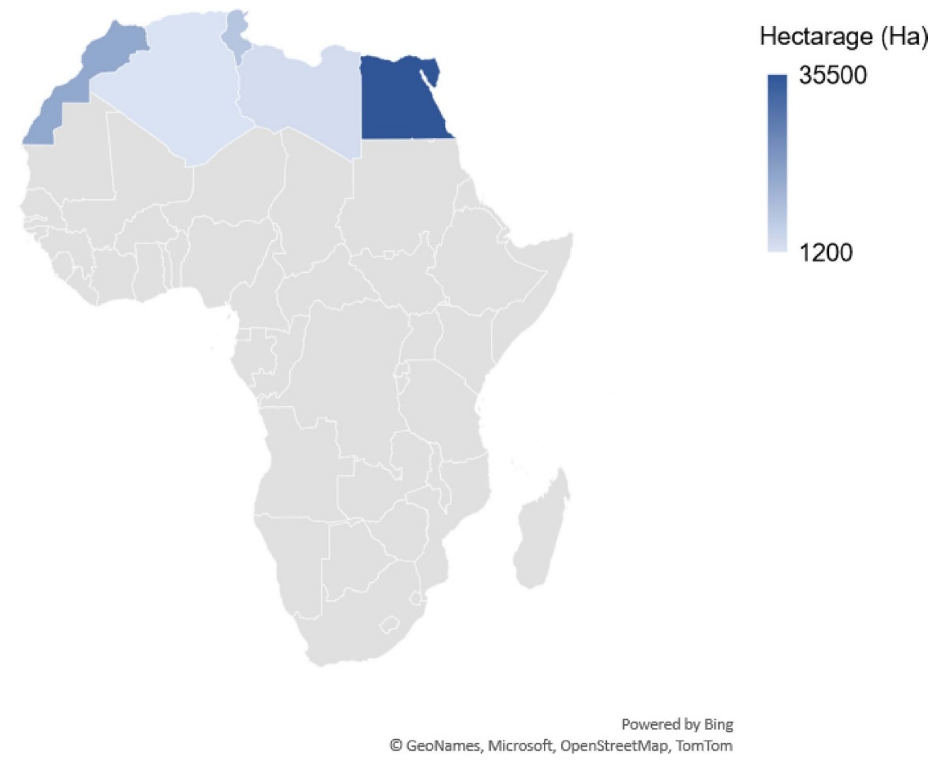

Figure 4. Unconventional water usage (pathway 4) across the continent.

effect on local low-level water users. Although there are challenges in North Africa, the data revealed that opportunities for improving irrigation development in the region are characterized by the availability of green energy, which can be used for water abstraction, conveyance and application for different irrigation technologies. Access to green energy, specifically solar energy, can be leveraged to provide low-cost renewable energy to support irrigation development. In addition, the green energy avenue can potentially support new players in the irrigation fraternity. Public—private partnerships (PPPs) can be fostered to create a new inclusive economic value chain that improves the FLID farmers' adaptation options (Taguta *et al* 2022). Extension services were quite pronounced in the region. The presence of extension services boosts information dissemination for best management practices. Climate-smart agriculture has a presence in the region. FLID farmers in Egypt used smart water meters for flow and usage monitoring. The technology facilitates real-time water usage and monitoring, thus assisting with irrigation scheduling. Real-time data-driven irrigation schedules promote water productivity and minimize energy consumption during abstraction, conveyance and delivery (Mudumbe and Abu-Mahfouz 2015). The next section looks at the opportunities and challenges faced across the continent at different scales.

3.3. Opportunities and challenges faced in Africa

We applied a simplistic word cloud tool for each region to generate a word tag representing the most prominent words based on frequency and relevance. Word cloud generation was based on full text analysis i.e. abstract, keywords and full text. The word cloud revealed heterogeneity across the continent. The heterogeneous nature of the continent presents opportunities for mapping and providing bespoke solutions at scale. The heterogeneity can be leveraged to holistically assess and identify bright spots and pitfalls that can be applied to other lagging regions. We assessed each geographical region's opportunities and challenges, and the word mining results revealed overlaps and minor variances.

3.3.1. Opportunities

North Africa

North Africa exhibited a pronounced presence of extension services and availability of green energy (figure 5). Extension services meet the information demands of farmers through communication technologies and improved management practices. The presence of extension services minimizes technological and management gaps. This is evidenced by increased maize yield in North Africa against a decrease in the harvestable area (Epule *et al* 2022). The availability of renewable green energy in North Africa augments the agricultural energy requirements

Figure 5. Summarised opportunities in implementing AWM practices in North Africa and the different sub-Saharan African regions.

in irrigated and rainfed systems. Energy is required for pumping irrigation water and for mechanization across scales.

SSA

Results in SSA exhibited overlaps than variances, hence this review provided an overview of the SSA opportunities. Identified AWM practices hinged on agronomic and soil management practices (figure 5). The prevalent practice in all the regions was crop rotations which, if judiciously practised, improve the infiltration capacity and the subsequent water-holding capacity of the soil. Additionally, crop rotations also minimises the buildup of crop-specific pests and diseases and improve the overall health and nutritional value of the soil. Another prevalent practice across the four sub-Saharan regions was CA, achieved through minimum soil tillage. These practices require commitment from the farmers, and considering that they are already implementing the practices, this provides an entry point to leverage for upscaling and out-scaling. Based on our findings, we opine that technology uptake in the regions provides a foundational basis and evidence to channel investment in extension services that drive knowledge dissemination and communication channels to reach a wider audience. Soil and water conservation practices were also prevalent in the SSA. Examples include rainwater harvesting and the use of contour bunds centred on runoff control planning /runoff disposal planning can be leveraged by providing prolonged storage facilities for water supply during drought periods.

3.3.2. Challenges

Observed challenges were nearly similar, with differences as expected due to the heterogeneous nature of the geopolitical regions. This section presents challenges encountered in each region and possible explanations for why this is the case. The challenges are summarised in figure 6.

North Africa

Challenges observed in North Africa were mainly policy-related and increasing competing interests in freshwater resources. The region has seen rapid economic expansion powered by energy supply and demand. Energy requirement (supply) has seen 20 million people access energy in rural and urban areas. The energy is primarily used for household utility (IEA 2020). Hydropower is the second most relied upon energy generation facility after LPG gas. However, competing interests reduce access to marginalized groups.

Furthermore, the high costs of solar PVs in the region (IEA 2020) inhibit the entrance of new players, suppressing the growth potential of new players in the renewable energy arena. This consequently affects the potential to use renewable energy at the local scale. Consequently, North Africa must improve its regulatory frameworks and energy tax policies to facilitate equal access to renewable energy equipment and infrastructure locally.

East Africa

The region is plagued by physical and socioeconomic factors affecting irrigation performance across the four AU-IDAWM pathways. CC has impacted agricultural growth in the region, and interventions are lacking to build more resilience (Matthews *et al* 2022). For example, when water is scarce, coordinated efforts are required to organize water use for improved efficiency and productivity. However, in the East African context, the ineffectiveness of WUA affects water productivity. The lack of coordination amongst FLID farmers sharing common pool resources negatively impacts water adequacy, consequently translating to poor AWM. Poor institutional coordination between the traditional authorities and WUA promotes disharmony that affects the collection of water fees that finances operation and maintenance (O&M) programmes. In addition, poor coordination affects participation. Dirwai *et al* (2019a), in their study, revealed that harmony amongst regulatory institutions improves farmers' willingness to participate and pay water fees. Land tenure limits access to tangible and intangible assets that can be used as collateral at financial institutions. To fully implement the AU-IDAWM pathways, national institutions must align with local-level water management and farming institutions. A trickle-down effect can be achieved through improved extension services provided these services are demand-led. Policy alignment and turning it into practice requires investment in extension services, which is currently inadequately funded. As of 1995, continued retrenchments and poor funding have reduced the extension works population to 2000 workers for the 45 districts in Uganda (Mwanje and Duvel 1998). Also, a recent report by AGRA (2023), stated that the average extension agent to farmer ratio ranges from 1:3000–1:10 000, representing low capacity across the continent. Land degradation negatively impacts soil fertility, water-holding capacity, and runoff control planning. The combined effects influence AWM because (1) poor soil integrity affects infiltration capacity and water holding capacity, thus minimizing plant available water in the soil profile, and (2) degraded lands are prone to forming gullies that complicate rainwater harvesting and catchment management. Compared to low-cost agronomic and soil management methods, expensive mechanical interventions are required for land reclamation and restoration. The expenses are beyond the reach of low household income farmer group that dominates in pathways 1 and 2.

West Africa

The challenges observed in West Africa stem from poor investment in irrigation development and AWM. This investment issue is multi-pronged

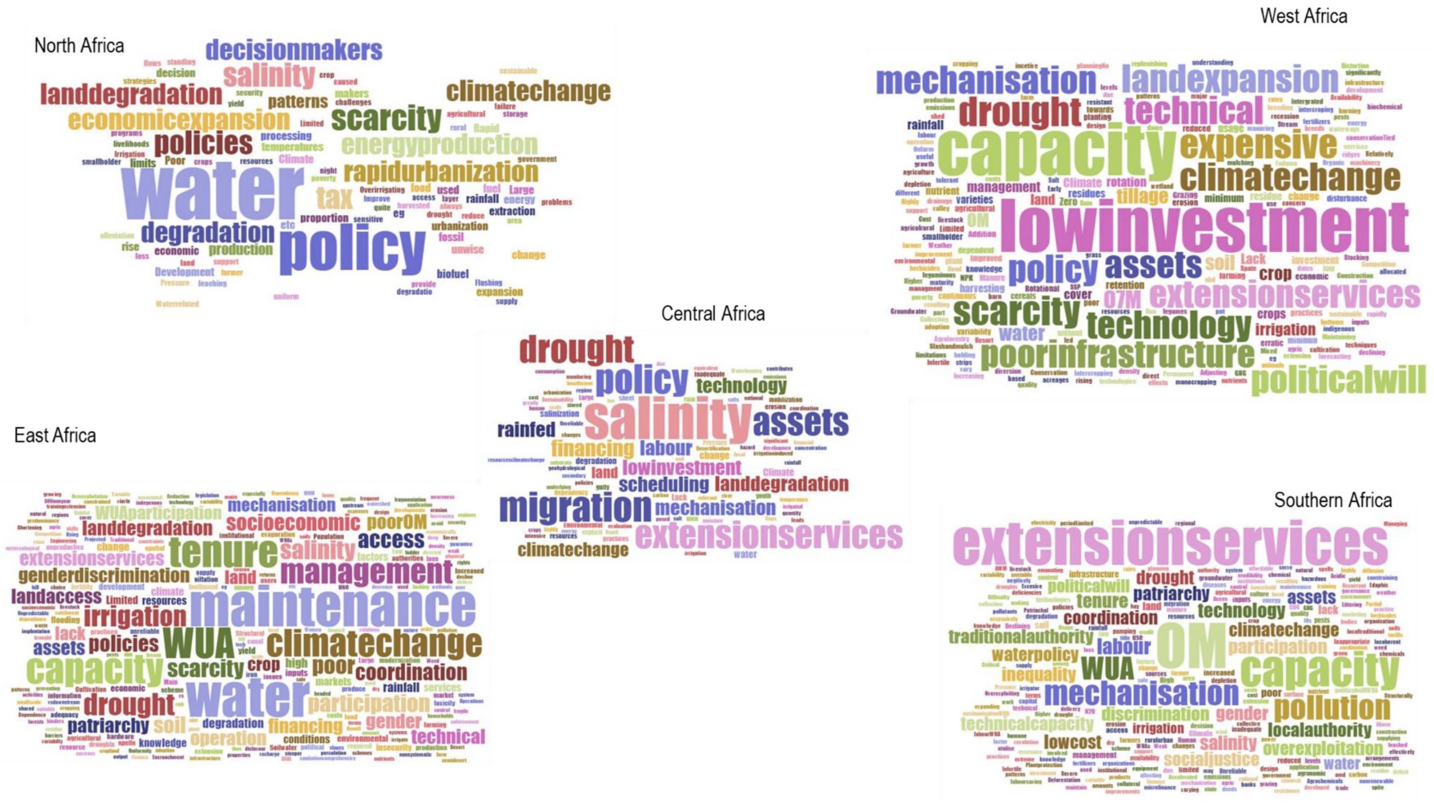

Figure 6. Regional challenges and barriers to effective AWM in Africa.

because it touches on the availability of funds for extension workers' capacitation, funds for extension services operations, and funds for farmers to acquire assets. Poorly trained extension workers cannot meet farmer demands, widening the technology and management gap locally (Anderson and Feder 2003). Also, a lack of funds blocked information and knowledge dissemination. Furthermore, a lack of financing inhibits asset acquisition which is important for mechanization. As stated above, under the opportunities section, CA and/or zero tillage agriculture dominate pathways 1, 2, and 3. It is important to mention that CA is a laborious practice. A non-mechanized system has a physical labour burden that discourages farmers from adopting the practice. Facilitating land tenure improves asset acquisition because farmers can use land as collateral for borrowing. This, in turn, boosts asset acquisition that contributes towards mechanization and improved investment in the land through soil and water conservation infrastructure. Political will plays an important role in developing strategies and implementing them.

Southern Africa

The prevalent word in the region was O&M. Southern Africa is characterized by pathway 2, i.e. FLID farmers concentrated in irrigation scheme setups. However, incapacitated WUAs and the poor participation of farmers in such organizations render the ineffective operation of the institutions. The WUA is mandated to collect water fees meant for O&M. O&M entails canal repair and silt removal for efficient water conveyance that subsequently improves spatial water adequacy and reliability (Molden and Gates 1990). Poor O&M procedures affect canal cleanliness that impact hydraulic efficiencies of the system; this consequently affects water adequacy (Renault 2000). Hydraulic inefficiencies generate instances where one part of the scheme is over-irrigated and the other under-irrigated (Lankford 2006). The question is, are the over-irrigated lands prepared to deal with excess water to divert it to the channel for continued reticulation to downstream users? Often that is not the case when WUAs are dysfunctional and fail to educate farmers, thus creating a management gap that impacts AWM. There exists a dearth of extension services creating disconnects between the farmers, farmer organizations in the form of WUAs, and traditional authorities in the irrigation schemes. Thus, the FLID pathway is plagued with a widening technological and management gap due to inadequate extension services. Another potential challenge is hinged on the low penetration of technology locally, which translates to poor mechanization. Mechanization at the local scale comprises farm implements and water pumps to abstract water from catchments, canals, and reservoirs to the field. Lack of support structures to mechanize the local level farmer dually affects AWM through unwillingness to adopt CA because of high labour requirements and inefficient laborious water conveyancing methods.

Central Africa

The prevalent words in the region were assets, salinity, migration, technology, and policy issues. Poor agronomic practices promote soil salinity. Saline soils require excess water to leach salts. Thus, one must apply excess water beyond the crop water requirements to flush the soils and create conducive conditions for plant growth. The excess water application is against the backdrop of scarce water resources driven by climate variability and rising demand. In addition, farmers in the region have a dual problem of salinity and a lack of irrigation technologies that can mitigate or promote optimal crop growth and effectively manage salinity. According to Sun *et al* (2012), drip irrigation technology can effectively utilize water whilst providing optimal leaching requirements for crop production. However, the expensive technology is often out of reach of the resources strained farmers. Policy interventions have significant impacts on AWM. However, in some cases, the policy and strategy dimension is silent, rendering irrigation development and AWM ineffective. For example, Cameroon does not have a well-spelt out irrigation policy (WorldBank 2020); hence water legislation is governed by the Water Law of 1999. The Water Law does not explicitly mention irrigation, and PPPs in the form of the Company for the Expansion & Modernization of Rice Cultivation at Yagoua (SEMRY) and the Northern Region Development Agency (MEADEN) govern irrigation development and the subsequent water governance (WorldBank 2020). SEMRY and MEADEN provide extension services to farmers in the northern regions. This is evidence of the poor political will to develop pro-public food production and irrigation development legislation. Supporting institutional agricultural infrastructure can alleviate poverty by empowering the two million smallholder families (Nkengne *et al* 2016) that bear the brunt of CC.

Another example is the absence of an irrigation policy in Equatorial Guinea. The country relies heavily on hydrocarbons, yet the global shift to green energy implies a diversification out of hydrocarbons to other sectors such as agriculture. Hence the country has been driven to revive the agricultural economy by initiating various intervention plans and strategies (GCF 2019). However, the country's closest policy and strategy intervention to irrigation development and AWM agenda is the REDD+ National Investment Plan for Equatorial Guinea, which seeks to reduce dependence on hydrocarbons and diversify the economy. The strategy lacks targeted development and runs the risk of an intervention that fails.

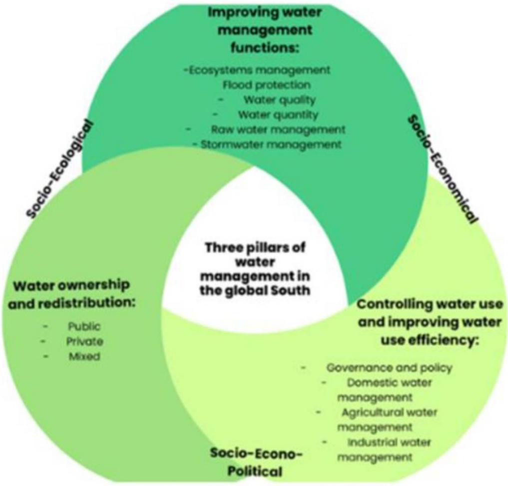

Figure 7. The three pillars that influence irrigation development and AWM across scales. When perfectly balanced, the pillars offer a gateway to effective AWM across multiple spatial and temporal scales. *Source*: (Smith *et al* 2023) John Wiley & Sons. [Copyright © 2023 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim].

3.4. Summative discussion on opportunities and challenges

Improved water adequacy, dependability, and reliability hinges on the physical, social, and economic factors prevalent in the different regions. Acknowledging the existence and interactions amongst socio-economical, socio-ecological, and socio-economic-political factors (figure 7) is catalytic to operationalising the AU-IDAWM framework for improved livelihoods and a healthy planet. The global south is fraught with challenges to AWM that range from ecosystem management, poor water licensing systems, land tenure, water availability and the subsequent water quality.

For pathways 1, 2, and 3, climate-smart agricultural practices/technologies are easy entry points for enhancing rainfed and supplemental irrigated agriculture and the subsequent ecosystem (Nkonya *et al* 2015, Hansen *et al* 2019). However, to fully maximise on the benefits, there exists a need to improve and increase access to tangible and intangible asset ownership across the gender divide. Tangible assets constitute of human and financial resources whilst intangible assets include access to information (Makate 2019). Accessing climate information can enhance AWM adoption through knowing the type of variety to plant depending on the rainfall and temperature seasonal forecast, pro-active preparation for protecting and designing built infrastructure (irrigation scheme revitalisation-PW3) that is structurally sound and adequate to withstand extreme events such as floods.

Socio-economic-political factors can potentially shape the policy direction which influences things like micro-financing and lending at favourable interest rates for FLID expansions and intensification. Socio-ecological and socio-economic factors are directly and/or indirectly linked to community settings. For example, operationalisation of Pathway 4 can be viewed as socially unacceptable in different communities. Therefore, to successfully operationalise the AU-IDAWM, niche regionally differentiated and context-specific scaling-up approaches such as functional scaling—up and political scaling-up are required. The former seeks to promote improved access to information and its dissemination channels for example, the training and increasing the number of extension worker to farmer ratio, whilst the latter involves implementing sustainable farmer activities that subsequently drive a bottom-up institutional and structural change (Gündel *et al* 2003, Pachico 2004, Makate 2019). Bottom-up institutional changes facilitate the designing of bespoke policies that match the local realities. The next section deep dives into the role of integrative investment planning for operationalising the AU-IDAWM framework.

4. Ways forward: investment planning

Considering the heterogeneous nature of the geopolitical regions, regionally differentiated and contextual targeted investment is required to promote fit-for-purpose interventions for different pathways across multiple scales. Investment plans should consider the bio-physical-socio-economic nature of the target regions. For example, to generate a solid investment plan, one has to take into consideration the interlinkages amongst variables such as; (1) government vs private sector relations (government vs privately owned irrigation projects); (2) climate issues in the form of wet-season irrigation vs year-round irrigation; irrigation vs rainfed production; (3) production intensity in the form of; expansion vs intensification of irrigation; and (4) production scales in the form of large-scale vs small-scale irrigation (Easter and Welsch 2019). We therefore propose an investment planning framework to facilitate decision-making across scales. The framework tries to harmonise the four interlinked variables mentioned above to each targeted investment under individual pathways so as to derive maximum benefits and minimise trade-offs across scales. The proposed investment planning decision framework provides bespoke financial interventions that facilitate operationalising the AU-IDAWM pathways. A typical example of the decision support tool is shown in figure 8 below.

The investment framework proposes financing of three dimensions namely; technological, social, and ecosystem functionalities. The three dimensions have different sub-interventions that potentially qualify for implementation under different pathways. For example, the technological intervention can be in water recycling and reuse across scales,

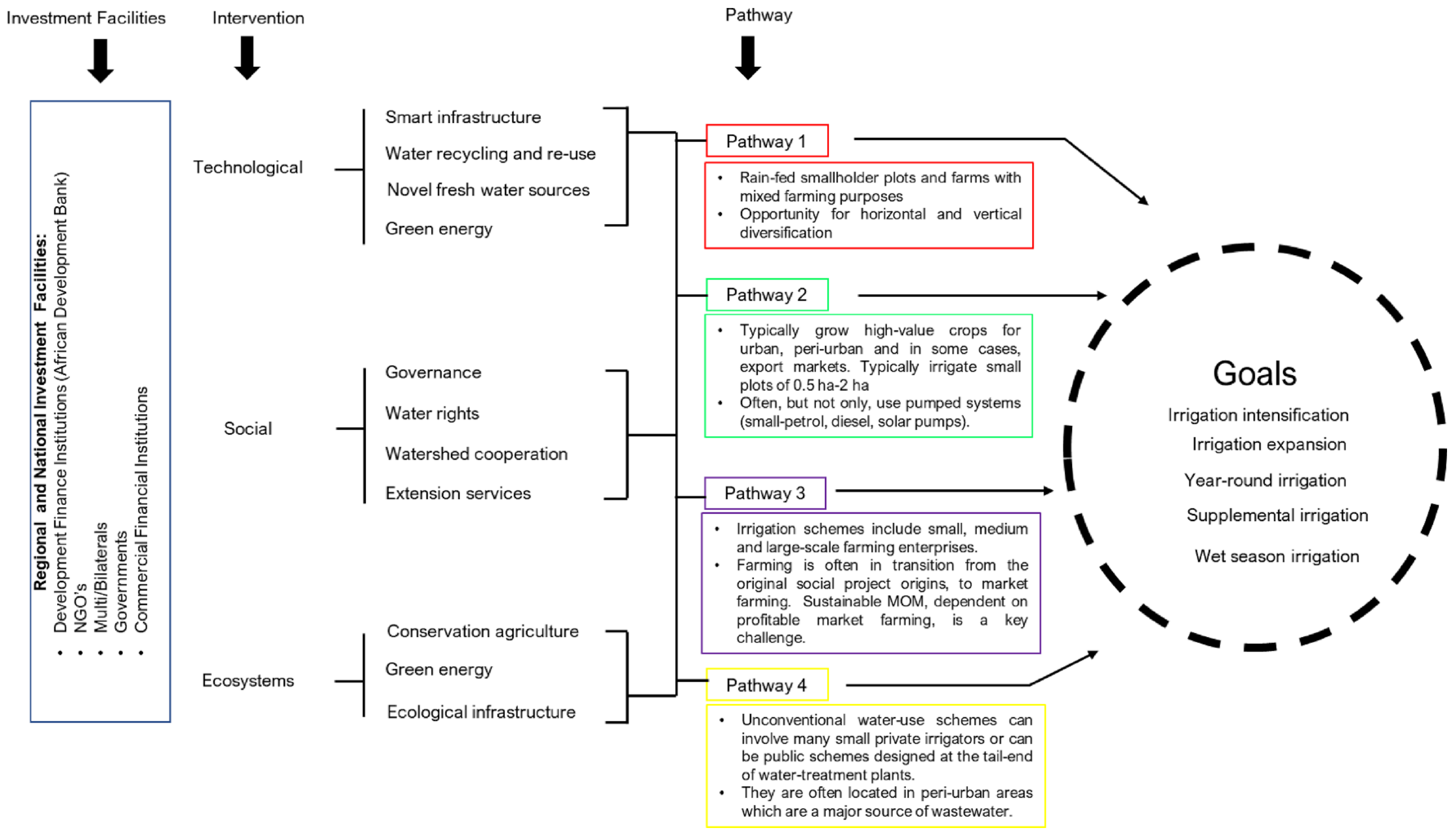

Figure 8. Typical investment planning decision support tool for bespoke financial interventions for the different AU-IDAWM pathways across scales.

enabling the operationalization of pathway 4. Typical examples include decentralised wastewater treatment systems that offer water treatment services for communities not connected to centralized municipality treatment centres as exemplified by a study by (Musazura *et al* 2015) in the KwaMashu area, Durban, South Africa. Other benefits of targeted technological investments in wastewater recycling are environmental surveillance during disease outbreaks and pandemics (Gwenzi 2022). The green energy intervention defines the energy requirement at scale. For example, green energy investment and rainwater harvesting at a sub-field scale will justify the acquisition of pumps to lift water from makeshift reservoirs and convey it to the field via earthen-lined canals. The pumps potentially have a positive gender inclusivity trickle-down effect.

The social intervention (second from the left column on the hierarchy) promotes governance, for example by creating WUA s under pathway 3. Typical investments should be dual targeting capacity building for extension services to bridge the technological gap and WUAs' best management practices to bridge the management gap. Regarding ecosystem services, encouraging scale-deep approaches that facilitate mind shifts can potentially drive people to invest and commit to promoting green infrastructure, subsequently improving the area's hydrology. The irrigation hydrological cycle needs to be improved through improved water conveyancing and water application efficiency that subsequently improves irrigation intensification output. The ecosystems approach is scalable and overlaps pathways 1, 2, and 3.

Also, since most smallholder farmers in Africa predominantly characterise pathway 2 (FLID), prioritizing the pathway is essential for facilitating pragmatic and actionable interventions. For example, the reviewed case studies reveal an inclination towards FLID; hence, targeted investments towards FLID should be facilitated for tangible outcomes (figure 9).

Figure 9 details three distinct FLID pathways namely; (1) modernized FLID characterised by farmers sharing common pool resources such as irrigation infrastructure, (2) individual FLID characterised by individual farmers innovating to maximise water abstraction using different low emission (movable pumps) and high emission technologies such as diesel and petrol pumps, and (3) modernized individual FLID farmers that utilise alternative low emission green energy sources such as solar pumps.

According to our analysis we opine that modernized FLID farmers could maximise the derived benefits by strengthening WUAs to effectively manage their irrigation quotas. WUA strengthening can be through capacity building by extension services through water user sensitization on the benefits of collection fees for O&M for improved water conveyancing efficiency. As for the individual FLID, there is a need for introducing the low-cost chameleon sensor for soil moisture monitoring. This minimises the burden of labour and the minimal use of high emission diesel and petrol pumps. Modernized FLID farmers require supportive financing mechanism for solar pump acquisitions. An enabling environment is key for providing flexible lending and interest rates over an agreed pay-back period.

Thus, we also propose another long-term intervention that goes together with financing criteria. The FLID intervention proposes additional financing in low-cost technological approaches and the digitization of agriculture at scale (see figure 9). The African Union can leverage Africa's surging mobile and internet penetration to utilise earth observation and automatic weather station data for informed irrigation scheduling. Decision support tools that can be presented in user-friendly dashboards can collect real-time satellite data for informing localised soil water stresses thus facilitating optimal irrigation to avert crop failure. Another opportunity lies in financing the production of impermeable low-cost, recyclable geosynthetic materials for canal repair and lining to improve conveyance efficiencies.

Our assertion on targeted investments challenges the conventional blanketed investment approach that looks at limited parameters such as investment suitability as outlined by Ringler *et al* (2023). Investment suitability for greening food production is dependent on a stable macro-economic environment, availability of accessible electricity [of which approximately 46% of the African population lacks access to energy (IREAN 2023)], and often the presence of an operating and functional green energy policy, all which are not fully present in African countries. Transitioning to green energy in low to middle-income countries and in this particular case FLID pathway is inhibited by the dominance of private investors in the green energy space. As such, private investment is more likely to overlook the lower-bottom vulnerable. The literature argues that PPPs have enhanced and improved financial flows to the vulnerable however, critics argue that public finance follows private finance (Ringler *et al* 2023) hence exacerbating the funding gap between those that can acquire and those that cannot.

5. Limitations of the study

This study is based on publicly available published literature accessed using a word-search strategy and specific criteria, which may have led to some relevant literature being excluded. This potential limitation may have impacted the range of issues presented. However, the authors have made every effort to

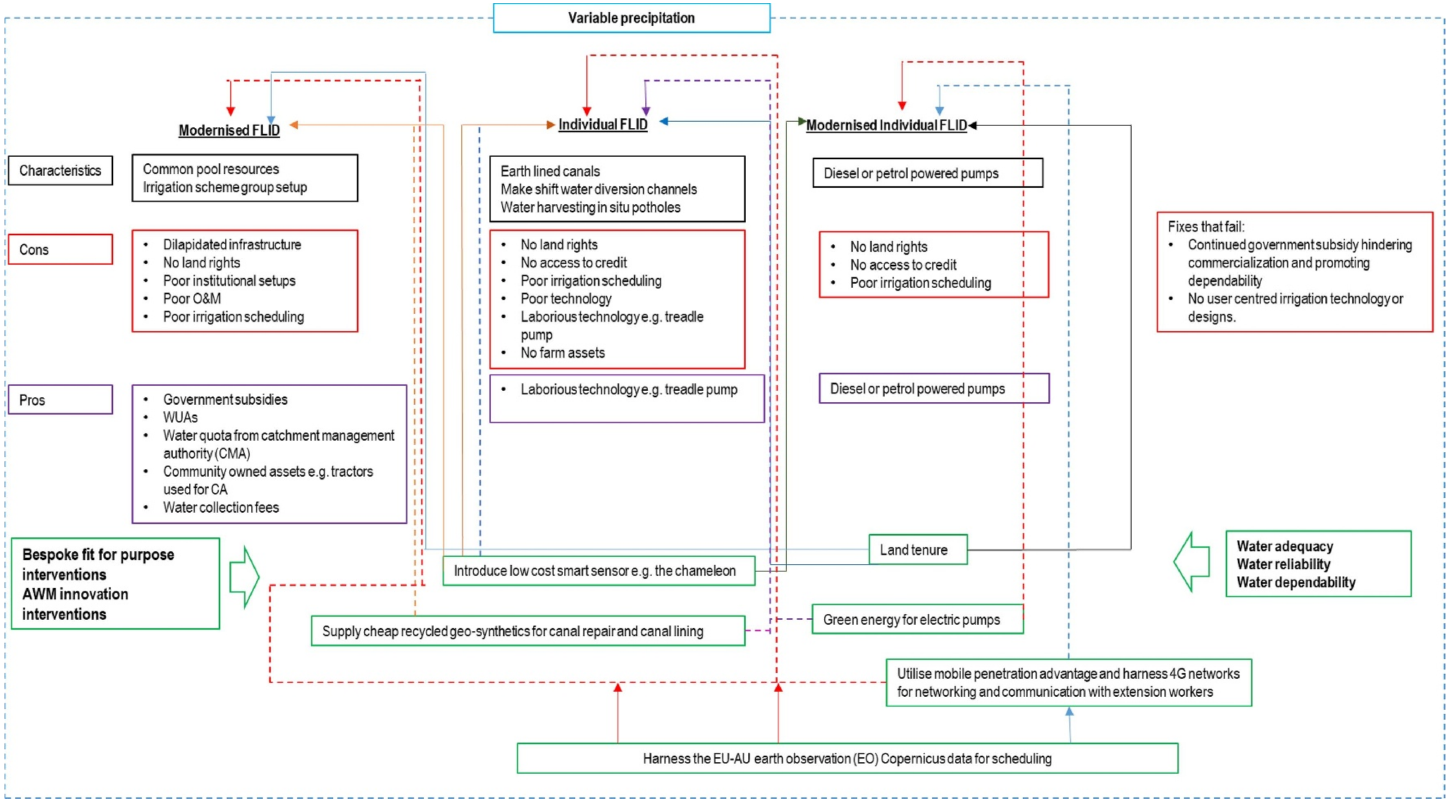

Figure 9. Actionable interventions for the FLID pathway that co-dominate Africa's food production systems. *Source*: authors.

be comprehensive and objective, addressing any overlapping considerations.

6. Conclusions and recommendations

Progressive and bespoke policies and legal frameworks are key in developing responsive, fit-for-purpose irrigation and AWM systems and practices. The study, recognising SSA is vulnerable to environmental and CC and growing water competition; suggested a wide variety of cross-cutting intervention measures. The regional AWM practices have overlaps and exhibit variation; therefore, the methods employed in each geopolitical region of the continent are adaptable at different spatial scales. We, therefore, conclude that:

- The commonly practised AWM strategies are zero tillage, mulching, and rainwater harvesting across pathways 1 and 2,
- There are overlapping bright spots across the regions of Africa. Identified overlapping opportunities are centred on local knowledge systems such as permanent soil cover, crop rotations and innovations such as CA,
- There exist a number of complex challenges across geopolitical regions that require bespoke interventions,
- Despite the bright spots, the FLID setup is a complex and dynamic theatre of activity shaped by different human behavioural patterns, influencing the success or failure of any strategy or policy implementation. Water governance structures are required in grouped FLIDs to facilitate water management, infrastructure, and provisions through adequate, reliable, and dependable supply. CC has severely impacted water dependability and subsequent adequacy. The available policies can innovate towards improving FLID, as illustrated below. Ideal pathways to innovation are low-cost and achievable pathways because of resource availability. The AWM innovations contribute to operationalizing the AU-IDAWM using low-cost and easy-to-understand inputs. We can test-run and further develop our investment planning matrix for effective operationalization of the AU-IDAWM pathways.

We recommend tailored financing approaches, for example promoting where relevant the establishment of green infrastructure for water conservation. As instituted in countries like Tunisia, demand-driven water-related policies facilitate flexibility in responding to changing situations. We hypothesize that demand-driven approaches promote fit-for-purpose interventions. The study also recommends bridging and documenting pathway operationalisation, specifically pathway 4 where data on hectarage irrigated by unconventional water is missing. Bridging the data gap will facilitate the operational and strategic decision-making to fully utilise unconventional water resources.

We opine that inclusive gender-sensitive irrigation plans that focus on sustainable irrigation development and management, underpinned by capacity building are potentially adequate enough to drive national IDAWM agendas. Numerous strategies that overlap under different government departments create an uncoordinated effort to achieve and operationalise the AU-IDAWM. The policy frameworks and legal instruments require a harmonized and directed effort towards a coherent policy and strategy. African governments are encouraged to utilize climate finance facilities to build capacities for resilience. The success of any strategy uptake depends on farmer dialogue, extension services and tailored dissemination. The climate information services and their subsequent dissemination channels can leverage low-cost communication platforms using smartphone facilities. In addition, relevant policy instruments can be communicated to local smallholder farmers. Policy issues such as land tenure are important because ownership improves access to credit, which one can use to finance irrigation infrastructure and farm machinery and implements that cut labour costs and time resources input for operationalizing CA. PPPs can potentially drive the adoption of the AU-IDAWM. Private partners can provide loans or credit to irrigators, and they can improve market access for local commodities. Marketed goods generate income that is invested back into land and water.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors have no conflict of interest to declare.

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

The authors **did not** use generative AI to write this manuscript

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