

EVALUATING TRADITIONAL AND IMPROVED WATER HARVESTING TECHNIQUES USING THE FAO AQUACROP MODEL

ÉVALUATION DES TECHNIQUES TRADITIONNELLES ET AMÉLIORÉES DE COLLECTE DES EAUX AU MOYEN DU MODÈLE FAO AQUACROP

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ABSTRACT

Agricultural Water Management is essential for mitigating climate-induced water scarcity. Water Harvesting Techniques offer practical field-level interventions, yet evaluating their impact often requires strategic modeling tools like FAO-AquaCrop, especially in data-constrained regions. This study presents a systematic literature review to frame the current state of FAO-AquaCrop-based WHT simulations. A targeted search of major databases identified a specialized body of literature, from which three primary modeling strategies were synthesized: (i) in-situ accumulation as irrigation events, (ii) soil hydraulic property modification via Curve Number adjustments, (iii) ex-situ storage coupling through external water balance integration.

Results indicate that while FAO-AquaCrop's one-dimensional architecture requires methodological "workarounds" to represent physical structures like infiltration trenches, its parsimonious design provides a functional framework for strategic planning. However, limitations regarding semi-quantitative soil fertility representation and the absence of native modules for diverse physical structures necessitate cautious interpretation. The findings suggest that AquaCrop is a suitable tool for preliminary assessments of WHT efficacy, facilitating a transition toward evidence-based implementation in remote agricultural systems. This review underscores the importance of rigorous calibration and highlights the potential for multi-model coupling to address landscape-scale hydrological dynamics in future research.

Keywords: Water harvesting techniques; Agricultural Water Management; Water balance; Soil fertility; Infiltration trenches.

RÉSUMÉ

La gestion de l'eau agricole est essentielle pour atténuer la pénurie d'eau induite par le climat. Les techniques de collecte des eaux offrent des interventions pratiques à l'échelle de la parcelle, mais l'évaluation de leurs effets nécessite souvent des outils stratégiques de modélisation tels que FAO-AquaCrop, en particulier dans les régions où les données sont limitées. Cette étude présente une revue systématique de la littérature afin de dresser l'état actuel des simulations de techniques de collecte des eaux fondées sur FAO-AquaCrop. Une recherche ciblée dans les principales bases de données a permis de recenser un corpus spécialisé de publications, à partir duquel trois stratégies principales de modélisation ont été synthétisées : (i) représentation de l'accumulation in situ sous forme d'événements d'irrigation ; (ii) modification des propriétés hydrauliques du sol par ajustement du

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numéro de courbe ; et (iii) couplage d'un stockage ex situ au moyen de l'intégration d'un bilan hydrique externe.

Les résultats indiquent que, si l'architecture unidimensionnelle de FAO-AquaCrop exige des « solutions de contournement » méthodologiques pour représenter des ouvrages physiques tels que les tranchées d'infiltration, sa conception parcimonieuse fournit un cadre fonctionnel pour la planification stratégique. Toutefois, les limites liées à la représentation semi-quantitative de la fertilité des sols et l'absence de modules natifs pour divers ouvrages physiques imposent une interprétation prudente. Les résultats suggèrent qu'AquaCrop est un outil adapté aux évaluations préliminaires de l'efficacité des techniques de collecte des eaux, facilitant ainsi la transition vers une mise en œuvre fondée sur des données probantes dans les systèmes agricoles éloignés. Cette revue souligne l'importance d'un étalonnage rigoureux et met en évidence le potentiel du couplage multimodèle pour prendre en compte, dans les recherches futures, la dynamique hydrologique à l'échelle du paysage.

Mots clés : Techniques de collecte des eaux; Gestion de l'eau agricole; Bilan hydrique; Fertilité des sols; Tranchées d'infiltration.

1. INTRODUCTION

Water is essential for crop production and agricultural development (Markland et al., 2017). Indeed, agriculture accounts for a large proportion of both green and blue water consumption among human activities (Ingrao et al., 2023). Green water refers to the rainwater stored in the soil profile as moisture, which is directly consumed by crops through evapotranspiration. Blue water, on the other hand, represents the fresh surface and groundwater resources – found in rivers, lakes, and aquifers – that are withdrawn and applied via irrigation to support crop growth (Falkenmark and Rockström, 2006). Water resources can become limited due to natural factors such as drought, or because of an imbalance between water supply and demand, leading to water scarcity. (Van Loon

& Van Lanen, 2013). Conversely, areas with erratic rainfall have to contend with extreme precipitation events, flash floods and inadequate drainage systems. In this context, agricultural water management is crucial for optimizing food production, improving water allocation, and mitigating the natural risks associated with extreme events (Salman et al., 2025). Agricultural water management can be approached from several perspectives: more practical approaches where technologies are implemented (Molden & Viala, 2008), such as Water Harvesting Techniques (WHTs) to improve water retention, storage, and productive use of rainfall and runoff, or more strategic approaches which involves the use of crop models (Kisekka et al., 2017) such as the FAO AquaCrop.

WHTs combine traditional land knowledge with scientifically based designs to divert runoff from non-productive land, known as catchment areas, to productive land to increase water availability for crop requirements (Rockström & Falkenmark, 2015). Defined as *“the process of concentrating precipitation through runoff and storing it for beneficial use”* (Oweis & Hachum, 2006; Mekuria, W., & Tegegne, D. 2023), technically, rainwater harvesting can be categorized into four primary scales: micro-WH, macro-WH, floodwater harvesting and rooftop and courtyard (Mekdaschi & Liniger 2013).

Micro-catchment systems (e.g., tied ridges or contour bunds) capture in-situ runoff within or immediately adjacent to the cropped area (Oweis & Hachum, 2006). In contrast, macro- and floodwater harvesting systems involve larger external catchment areas, where runoff is diverted from ephemeral streams or slopes and distributed across cultivated fields. Rooftop and courtyard systems involve the localized collection of runoffs from impermeable surfaces, often for storage in tanks to support supplemental irrigation or domestic needs. These systems are defined by three fundamental characteristics: the ratio of the catchment area to the cultivated area, conveyance efficiency, and soil or reservoir storage capacity (Rockström & Falkenmark, 2015).

While experiments and practical applications of WHTs proved their effectiveness under a huge variety of natural and socioeconomic conditions, evaluating the potential benefits and limitations prior to interventions is surely a useful complementary activity. Among the many available tools, FAO's AquaCrop can be considered one of the most suitable for drought-prone and water-scarce regions where data availability is limited. WHTs are usually implemented in remote rural areas that national research institutions struggle to cover with data sensors. AquaCrop is a valid model because, even with limited data input, it can generate simulations with a high degree of credibility, and its output can generate relevant data to inform evidence-based decision-making processes (Salman et al., 2025).

The tool is based on the soil-plant-atmosphere continuum, where the final yield is the product of biomass development generated by water transpired by the crop canopy and absorbed from soil moisture (Salman et al., 2021). It has been used for various purposes and in many contexts, from scenario projections to changes in field management, resulting in the ability to adapt to many situations and implement effective water management strategies and practices (Salman et al., 2025).

The aim of this study is to evaluate how computer models can be used to inform WHT implementation by focusing specifically on the FAO-AquaCrop model and the simulation of specific micro, macro and rooftop WHT. By reviewing existing literature, the study aims to define the approaches used to simulate the effects of WHTs on crop development, identify the modelling strategies applied, and evaluate their strengths and weaknesses. Furthermore, the review seeks to facilitate the transition from speculative planning to evidence-based implementation, support the development of technical training materials for practitioners, and enable the refinement of farm-level water-management strategies to ensure long-term food security under changing climatic conditions.

2. METHODOLOGY

To systematically map and critically evaluate the state-of-the-art in simulating WHTs within the FAO-AquaCrop framework, a targeted literature review was conducted by following the four phases of the PRISMA methodology for systematic reviews: identification, screening, analysis and discussion. The search was executed across major electronic scientific databases, including Scopus and Science Direct, capturing relevant literature published up to May 2026.

2.1 Identification: Search Strategy and Syntax

The search strategy was designed to pair the specific crop growth model ("aquacrop") with a comprehensive array of terms encompassing both generic WHT concepts and localized/specific physical techniques (e.g., contour bunds, spate irrigation). The exact boolean search string deployed across the databases was as follows:

("water harvesting" OR "rainwater harvesting" OR "runoff harvesting" OR "micro-catchment" OR "contour bund" OR "terracing" OR "in-situ conservation" OR "spate irrigation") AND ("aquacrop")

To complement this search, other papers – already known by the authors – were considered.

2.2 Screening: Inclusion and Exclusion Criteria

The resulting document pool was screened through a multi-stage process (title, abstract, and full-text evaluation) based on strict eligibility criteria to filter out non-simulation or tangential studies. Duplicates were removed and the following inclusion criteria were applied during the screening phase:

1. Peer-reviewed journal articles or official conference proceedings. Hence, grey literature, book chapters and editorial notes were excluded from the analysis;
2. Documents published in English;
3. Studies where the FAO-AquaCrop model was explicitly parameterized, calibrated, or executed to quantify the impacts of at least one WHT. Soil-water conservation techniques were

excluded. For example, Nyakudya and Stroosnijder (2014) simulated the AquaCrop outputs' sensitivity also to changes in CN, but they did not explicitly aim to represent a specific WHT practice; therefore, it was excluded from the papers considered. In general, studies mentioning FAO-AquaCrop or WHT merely as a conceptual recommendation without presenting numerical simulation workflows are excluded.

2.3. Analysis: Data Extraction and Synthesis Framework

A total of 9 studies strictly met the inclusion criteria and were retained for full-text analysis, representing a highly specialized and focused body of literature. To systematically answer the research questions, data were extracted into a standardized matrix capturing: the geographic focus, the crop types investigated, the version of the AquaCrop model utilized, if calibration and/or validation was conducted, and if experimental data were used to set up the model.

Finally, the identified modelling workflows were synthesized and classified into four distinct operational strategies based on how they adapt AquaCrop's one-dimensional (1D) point-scale architecture to simulate spatial hydrological processes:

- In-situ water accumulation: field bunds to eliminate runoff, floods as irrigation events.
- Soil properties modification: Alteration of soil hydraulic properties, curve numbers (CN), and management practices that influence evaporation and soil moisture conservation (e.g., mulching).
- Ex-situ water accumulation: Coupling external catchment or pond storage calculations with AquaCrop's irrigation modules.

This structured approach ensures transparency and reproducibility in characterizing the current capabilities and boundaries of AquaCrop-based WHT modelling

3. RESULTS: WH MODELING STRATEGIES IN FAO-AQUACROP

The nine studies identified provided a comprehensive overview of how the FAO-AquaCrop model is currently deployed to evaluate WHT interventions. Despite the limited number of studies, the results highlight a sophisticated range of simulation workflows designed to overcome the model's inherent point-scale limitations. Specifically, the literature identifies four primary methodologies for representing the hydrological impact of WHT (Table 1): surface boundary manipulation and water accumulation for in-situ capture of macro WHT, modification of soil hydraulic parameters for micro WH, external coupling for ex-situ storage WHT.

3.1 Modification of surface hydraulic parameters in micro-WHT

Biazin et al. (2012), Setti et al. (2023) and Wolka et al. (2021) effectively simulated the impact of micro-WH in AquaCrop by modifying the representation of surface runoff within the Field Management module to maximise water infiltration. Biazin et al. (2012) and Setti et al. (2023) simulated the impact of tied ridges by suppressing runoff losses. Specifically, Biazin et al. (2012) assumed a zero-runoff condition for tied-ridge simulations and contrasted this with a Curve Number (CN) of 88, which was used to represent traditional tillage. Similarly, Setti et al. (2023) simulated this effect by minimising the CN to its lower limit in the model, forcing all rainfall to be treated as potential infiltration into the soil profile. Wolka et al. (2021), on the other hand, simulated a similar in-situ practice — namely soil bunds — by utilising the homonymous "soil bunds" option specific to AquaCrop's field management settings. As their field structures consisted of an embankment coupled with a 50 cm deep trench, they adjusted the bund height parameter to 0.50 m, representing the combined volumetric storage capacity of the trench-bund system. This configuration successfully simulated near-zero surface runoff, consistent with field observations where such structures captured approximately 90% of runoff on steep slopes.

Table 1. Summary of WHT modelling strategy adopted in FAO AquaCrop

Strategy	Mechanism	Parameters Modified	Key References	Main Modeling Limitation
Soil Surface properties Modification	Alteration of soil physical parameters (e.g., hydraulic conductivity, Curve Number) to minimize soil evaporation (E) and optimize soil moisture retention.	CN, Mulch, Soil Hydraulic Conductivity	Biazin et al. (2012); Setti et al. (2023); Wolka et al. (2021)	Requires high-quality field data for soil calibration. The "suppression" of CN disregards rare overflows.
Ex-Situ Storage	Simulating external storage systems (e.g., farm ponds, micro-dams, rooftop). Water collected ex-situ is routed back into AquaCrop as supplemental irrigation schedules.	Irrigation Schedule Modules	Villani et al. (2018); Durodola et al. (2020); Mandal et al. (2020); Kimera et al. (2018); Hernandez Rosales et al. (2023)	Requires external data or software to simulate water harvested.
In-Situ Bunds	Modification of field surface hydrology (e.g., surface bunds height to prevent runoff and force infiltration, water accumulated or floods as an irrigation event).	Surf Bunds, CN, Floods as irrigation events	Renzi et al. (2023);	Cannot simulate spatial unevenness within the plot.

3.2 External coupling for ex-situ storage

Unlike in-situ WHT, ex-situ storage requires an external hydrological balance to determine the volumes available for irrigation. The source of the harvested water can be either simulated via additional modelling workflows (e.g. Durodola et al., 2020; Mandal et al., 2020; Hernández Rosales and Lutz, 2023) or inferred from field data interviews or other source of data (e.g. Villani et al., 2018). Analyzing the literature showed that AquaCrop has also been used for dimensioning WHT ponds (e.g. Kimera et al., 2018).

Ex-situ WH such ponds and dams have been considered in AquaCrop studies. For example, Mandal et al. (2020) utilised a simulation-optimisation framework in which a distributed hydrological model calculated daily inflows to check dams. These data then served as input for AquaCrop, which simulated crop responses to various irrigation schedules generated by an optimiser aiming to maximise total yield. Similarly, Kimera et al. (2018) simulated soil moisture during the critical growth stages of maize by predicting yields for different storage pond sizes under actual rainfall patterns to identify the optimal pond capacity to maximise economic benefits. Finally, Villani et al. (2018) investigated a sand dam irrigation system in Ethiopia and evaluated yield and crop water productivity under different irrigation and fertilization scenarios. The modelling workflow involved simulating furrow irrigation with schedules triggered at an 80% depletion threshold of readily available water. This approach enabled the authors to determine whether yield gaps were primarily caused by physical water scarcity from the sand dam or by constraints in soil fertility, demonstrating the model's effectiveness in environments with multiple stressors.

The AquaCrop model has also been applied to simulate rooftop WH systems. Durodola et al. (2020) modelled rooftop WHT in Uganda using a cascading calculation approach. In Durodola et al. (2020), the Rational Method was applied externally to quantify the maximum harvestable volume from specific roof catchments. This volume was then adjusted by subtracting domestic water priorities to determine the net 'blue water' available for agriculture. AquaCrop was then used to simulate the irrigation requirements and yield responses of four staple crops. Coupling the external storage balance with the model's irrigation scheduler enabled the identification of the maximum cultivable land area supported by the harvested surplus. Finally, Hernández Rosales and Lutz (2023) first calculated potential rooftop collection volumes based on climate classifications (dry, normal and wet years) and then used AquaCrop to determine the net irrigation requirements for staple crops. By linking these two values, the specific area of cultivable land that can be supported solely by harvested rainwater was established

3.3 Macro-catchment WHT in-situ water accumulation

Strategies for WH aim to reduce runoff velocity and enhance soil infiltration capacity. This increases the amount of water in the soil that is available for plant transpiration. One notable methodological approach to simulating these dynamics is to convert discrete runoff events into supplemental irrigation inputs. For example, Renzi et al. (2023) monitored a 6.3 km² upstream watershed and derived an experimental runoff coefficient of 0.19. In the AquaCrop environment, this was simulated by triggering a 45 mm surface irrigation event whenever the cumulative basin runoff (equivalent to approximately 0.86 mm of net rainfall) reached the system's storage capacity. To account for field heterogeneity and structural vulnerability, the authors compared a 'high-efficiency' scenario (45 mm application) with a 'low-efficiency' scenario (30 mm), simulating potential failures or breaches in earthen embankments. Furthermore, the physical retention of water within the plot was modelled using the Field Management module, in which 1-metre-high earthen bunds were parameterised to reduce the runoff coefficient within the cultivated area, thus forcing the infiltration of both direct rainfall and harvested inflows.

4. DISCUSSION

4.1 The Role of Calibration and Validation in Model Reliability

The systematic review of the identified literature emphasizes that the transition from a generic simulation tool to a robust decision-support engine depends fundamentally on a rigorous calibration and validation process. This stage is crucial for reducing the inherent uncertainties associated with input data and model structure (Mandal et al., 2020). While AquaCrop utilizes several "conservative" parameters that remain stable for a given species, many others are highly site-specific and depend on local cultivars, such as the Awassa BH540 maize in Ethiopia (Villani et al., 2018), and specific soil-water-environment interactions. Calibration against observed field data, such as canopy cover development and biomass accumulation, ensures that the model accurately reproduces the biophysical processes of the site (Wolka et al., 2021). Furthermore, a well-validated model provides the necessary confidence for policymaking, allowing researchers to distinguish between water-limited and nutrient-limited yield gaps. This distinction is vital for determining whether a lack of productivity stems from physical water scarcity or from soil fertility constraints that WHT alone cannot resolve (Villani et al., 2018).

4.2 Multi-Model Coupling and Comparative Modeling Strategies

A central theme emerging from the intercomparison of AquaCrop with more complex deterministic models, such as APSIM, DSSAT, or EPIC, is the balance between biophysical detail and operational parsimony (Wambua et al., 2026). AquaCrop's water-driven approach, which derives biomass directly from transpiration via a normalized water productivity index, makes it exceptionally suited for data-scarce environments where the high parameter requirements of carbon-driven models cannot be met (Durodola et al., 2020). However, the model's 1D point-scale architecture remains a significant bottleneck for assessing landscape-scale interventions. To overcome this, recent studies have successfully employed hybrid modeling frameworks, coupling FAO- AquaCrop with watershed-scale models such as SWAT (Wambua et al., 2026). In these configurations, the hydrological model manages the complex runoff routing and storage dynamics (e.g., in sand dams or check dams), while AquaCrop provides a high-fidelity simulation of the crop's physiological response to the harvested water. This synergy fills the spatial gaps that neither model could address with the same level of precision independently.

4.3 Soil Fertility, Climate Adaptation, and Structural Boundaries

Despite its versatility, AquaCrop's semi-quantitative approach to soil fertility remains a notable limitation. By collapsing complex nutrient cycles (e.g., Nitrogen or Phosphorus) into a single stress index expressed as a percentage reduction in canopy growth, the model may fail to capture the long-term impacts of soil degradation or nutrient leaching common in high-runoff environments, or vice

versa fertile sediment deposition from upstream run-off. This limitation is compounded by the structural difficulty in representing specific WHT interventions. Since the model lacks native modules for infiltration trenches, researchers are often forced to adjust the "soil bund height" as a proxy for the system's total storage capacity (Wolka et al., 2021). While this "workaround" provides reasonable short-term estimates, it may ignore the long-term physical feedback of soil erosion on productivity (Vema et al., 2022; Wambua et al., 2026).

Regarding climate change adaptation, the reliance on empirical relationships to simulate the effects of elevated CO₂ may not fully account for the complex interactions between rising temperatures and vapor pressure deficits in open-field conditions (Villani et al., 2026). Additionally, the lack of comprehensive meteorological data in many arid regions frequently necessitates the use of simplified methods, such as the Hargreaves equation, for calculating reference evapotranspiration (ET₀), which introduces further uncertainty into multi-decadal projections (Setti et al., 2023). Finally, most simulations assume stationarity in management and soil properties, potentially overlooking the adaptive capacity of farmers or the gradual decline in WH structure efficiency over time (Renzi et al., 2023). Consequently, AquaCrop is best utilized as a tool for strategic adaptation planning, provided that its structural boundaries are carefully considered during the interpretation of results.

CONCLUSIONS AND FUTURE PERSPECTIVE

This systematic review indicates that while the integration of WHT within the FAO-AquaCrop framework is currently limited to a specialized body of literature, the model demonstrates a capacity to simulate the hydrological impacts of these technologies on crop development. By analyzing the current body of literature, the study identified three distinct modelling strategies – in-situ accumulation, soil parameter modification, ex-situ storage coupling – that enable methods to overcome the model's native one-dimensional limitation. These approaches demonstrate that the water-driven approach of AquaCrop is particularly robust for evaluating WHT in data-scarce environments in the Global South, where expensive and logistically challenging field trials are often unfeasible. These findings suggest that FAO-AquaCrop can serve as a supportive tool for the strategic planning of water harvesting interventions, particularly to explore climate change adaptation scenarios in water-scarce regions.

However, transitioning from experimental simulation to large-scale implementation reveals critical structural limitations. The model's semi-quantitative approach to soil fertility, and its lack of native modules for complex structures such as infiltration trenches, remain significant obstacles. Furthermore, as AquaCrop does not consider the long-term physical effects of soil erosion or structural degradation, current productivity estimates may be overly optimistic. To address these issues, future research should shift towards hybrid modelling frameworks. Coupling AquaCrop's high-fidelity crop response with watershed-scale hydrological models, such as SWAT, is essential for capturing the spatial interdependencies and upstream and downstream impacts of water harvesting at the catchment level.

In conclusion, refining these modeling workflows is a vital step toward evidence-based agricultural management. Despite its current limitations, AquaCrop remains a highly accessible and credible tool for informing decision-making processes in vulnerable regions. By integrating more dynamic adaptive management scenarios and fostering multi-model synergies, the scientific community can provide the technical foundations necessary to scale WHT, ultimately ensuring long-term food security and climate resilience.

CRedit author statement

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