# Deliverable N.: D3.2.1 / D3.2.2

# BMP intervention scenarios

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| Funding source: | EU Initiative on Climate-relevant Development Smart Innovation Through Research in Agriculture in developing countries – DeSIRA |
| Project Acronym: | WATDEV |
| Project Full Title: | Climate Smart WATer Management and Sustainable DEVelopment for Food and Agriculture in North-East Africa |
| CRIS Ref.: | FOOD/2021/425-767 |
| Project duration: | 54 months |

Published by the WATDEV Consortium
Dissemination Level: Public

This project has received funding from the European Union's
DeSIRA Initiative (Development Smart Innovation through Research in Agriculture)

## WATDEV CONSORTIUM

The project consortium is comprised of:

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| **EGYPT** | Heliopolis University (HU) |
| **ETHIOPIA** | Water and Land Resource Centre (WLRC) |
| **FINLAND** | Finish Environment Institute (SYKE) |
| **ITALY** | Centro Internazionale di Alti Studi Agronomici Mediterranei di Bari (CIHEAM-Bari) |
| **ITALY** | Italian Research Council (CNR) |
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| **THE NETHERLANDS** | International Soil Reference and Information Center (ISRIC) |
| **UGANDA** | Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA) |

## DOCUMENT INFORMATION

| | | | |
|---|---|---|---|
| **Project number** | FOOD/2021/425-767 | Acronym | WATDEV |
| **Full title** | Climate Smart WATer Management and Sustainable DEVelopment for Food and Agriculture in North-East Africa | | |
| **Project URL** | www.watdev.eu | Document URL | |
| **Implementation Agency** | AICS (Italian Agency for Development Cooperation) | | |

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|---|---|---|---|---|
| **Deliverable** | Number | D3.2.1<br>D3.2.2 | Title | BMP intervention scenarios |
| **Project Activity** | Number | A3.1<br>A3.2 | Title | A3.1 – Integrated and multi-thematic modelling<br>A3.2 - Carrying out a participatory identification of best suiting and feasible scenarios for the implementation of BMPs and Innovations |

| | | | | |
|---|---|---|---|---|
| **Date of delivery** | Contractual | M49 | Actual | M54 |
| **Status** | Version 1.0 | | Final | |
| **Final review** | 26/06/2026 | AICS check | mm.dd.aaaa | |
| **Type of document** | ☐ prototype<br>✓ **report**<br>☐ demonstration<br>☐ other | | | |
| **Dissemination level** | ✓ **public**<br>☐ confidential | | | |

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|---|---|---|---|---|
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|---|---|
| **Abstract (for dissemination)** | The Climate Smart WATer Management and Sustainable DEVelopment for Food and Agriculture in East Africa (WATDEV) project aims to enhance sustainability of agricultural water management and resilience of agro ecosystems to climate change in East Africa and Egypt. The executive agency is AICS (Agenzia Italiana per la Cooperazione e lo Sviluppo); the leading scientific institution CIHEAM-BARI is working with local partners ASARECA (Strengthening Agricultural Research in Eastern and Central Africa), KALRO (Kenya Agricultural and Livestock Research Organization), WLRC (Water and Land Resource Centre, Ethiopia), WRC (Water Research Centre, Sudan) and HU (Heliopolis University, Egypt). The modelling component is led by ISRIC (International Soil Reference and Information Centre, The Netherlands), together with SYKE (Finnish Environment Institute, Finland) and CIHEAM-Bari (Italy). The specific objectives include: (1) to improve the knowledge and capacity of National Ministries and Research Institutions in agricultural water management; and (2) to support farmers and local actors, cooperatives and Water User Associations in implementing innovative and sustainable solutions and improve skills on water management.<br><br>To support these objectives, the modelling partners has developed a modelling toolbox (hereafter called WATDEV Toolbox) capable of analysing the effect of the selected Best Management Practices (BMPs) on key environmental, agricultural and social-economic indicators. During a series of stakeholder workshops in March, April and May 2024, local and regional stakeholders were consulted to identify their preferred BMPs, implementation scenarios and performance indicators. These BMPs and scenarios were subsequently adapted and parameterized to fit the requirement and capabilities of modelling toolbox. The same stakeholders were presented with preliminary impact results during workshops held in |

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| | November and December 2025, where they proposed changes to BMP implementation and indicated the most relevant KPIs for subsequent analysis. They were also able to explore the technical parameters underlying the modelling and assessment during regional training events held in February and May 2026.<br><br>This deliverable reports on the BMPs, and presents an assessment of their impacts on biophysical and socioeconomic Key Performance Indicators (KPIs), and a combined performance assessment using Multi-Criteria Analysis (MCA), using the WATDEV Toolbox. The selected BMPs fall into three main categories:<br>• Changes in cultivation practices, including the introduction of new crops, crop rotations, and improved fertilization strategies;<br>• Agroforestry practices, involving the integration of trees and perennial crops with annual cropping system, as well as the using trees for erosion control;<br>• Water User Association (WUA) interventions, aiming at increasing water availability and improving water use efficiency through irrigation system improvements and the adoption of water-saving practices.<br><br>Although these BMPs categories were common across the study sites, their specific implementation details varied considerably, reflecting the need for customization by local actors.<br><br>The results indicate that the BMPs that are expected to bring improvements to each site are related with current conditions. In Egypt, where limited water resources are a concern, the best-performing BMP was a WUA intervention designed to decrease water use (drip irrigation); while in Kenya and Sudan, where water resources are mostly limited by distribution, the best-performing BMPs were also WUA interventions, but designed to increase water availability. In contrast, Agroforestry BMPs were found to perform the best as they provide improvements for crops and soils which match the concerns of local managers. The assessment also highlighted how BMPs with low performance might be improved with technical changes. |
| **Keywords** | Best Management Practices; BMP scenarios; key performance indicators, model simulations. |

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## Acronyms and Abbreviations

| | |
|---|---|
| AICS | Italian Agency for Development Cooperation |
| ASARECA | Association for Strengthening Agricultural Research in Eastern and Central Africa, Uganda |
| BMP | Best Management Practice |
| CIHEAM | Centre International de Hautes Etudes Agronomiques Méditerranéennes, Italy |
| CNR-IPSP | Consiglio Nazionale delle Ricerche, Italy |
| DOA | District Office of Agriculture |
| EU | European Union |
| HU | Heliopolis University, Egypt |
| ISRIC | International Soil Reference and Information Center, The Netherlands |
| KALRO | Kenya Agricultural & Livestock Research Organization, Kenya |
| KPI | Key Performance Indicator |
| KU | Khartoum University, Sudan |
| MALR | Egyptian Ministry of Agriculture and Land Reclamation |
| MCA | Multi-criteria Analysis |
| NIA | National irrigation Authority, Kenya |
| SMA | Sudan Meteorological Authority, Sudan |
| SOM | Soil Organic Matter |
| STI | Science, Technology, and Innovation |
| SWAT | Soil and Water Assessment Tool |
| SYKE | Finnish Environment Institute, Finland |
| TARDA | TAna River Development Authority, Kenya |
| WATDEV | Climate Smart WATer Management and Sustainable DEVelopment for Food and Agriculture in North and East Africa |
| WLRC | Water and Land Resource Center, Ethiopia |
| WRC | Water Research Centre, Sudan |
| WUA | Water Users’ Association |
| WUE | Water-Use Efficiency |

# Executive Summary

The Climate Smart WATer Management and Sustainable DEVelopment for Food and Agriculture in East Africa (WATDEV) project aims to enhance sustainability of agricultural water management and resilience of agro ecosystems to climate change in East Africa and Egypt. The executive agency is AICS (Agenzia Italiana per la Cooperazione e lo Sviluppo); the leading scientific institution CIHEAM-BARI is working with local partners ASARECA (Strengthening Agricultural Research in Eastern and Central Africa), KALRO (Kenya Agricultural and Livestock Research Organization), WLRC (Water and Land Resource Centre, Ethiopia), WRC (Water Research Centre, Sudan) and HU (Heliopolis University, Egypt). The modelling component is led by ISRIC (International Soil Reference and Information Centre, The Netherlands), together with SYKE (Finnish Environment Institute, Finland) and CIHEAM-Bari (Italy). The specific objectives include: (1) to improve the knowledge and capacity of National Ministries and Research Institutions in agricultural water management; and (2) to support farmers and local actors, cooperatives and Water User Associations in implementing innovative and sustainable solutions and improve skills on water management.

To support these objectives, the modelling partners has developed a modelling toolbox (hereafter called WATDEV Toolbox) capable of analysing the effect of the selected Best Management Practices (BMPs) on key environmental, agricultural and social-economic indicators. During a series of stakeholder workshops in March, April and May 2024, local and regional stakeholders were consulted to identify their preferred BMPs, implementation scenarios and performance indicators. These BMPs and scenarios were subsequently adapted and parameterized to fit the requirement and capabilities of modelling toolbox. The same stakeholders were presented with preliminary impact results during workshops held in November and December 2025, where they proposed changes to BMP implementation and indicated the most relevant KPIs for subsequent analysis. They were also able to explore the technical parameters underlying the modelling and assessment during regional training events held in February and May 2026.

This deliverable reports on the BMPs, and presents an assessment of their impacts on biophysical and socioeconomic Key Performance Indicators (KPIs), and a combined performance assessment using Multi-Criteria Analysis (MCA), using the WATDEV Toolbox. The selected BMPs fall into three main categories:

- Changes in cultivation practices, including the introduction of new crops, crop rotations, and improved fertilization strategies;
- Agroforestry practices, involving the integration of trees and perennial crops with annual cropping system, as well as the using trees for erosion control;
- Water User Association (WUA) interventions, aiming at increasing water availability and improving water use efficiency through irrigation system improvements and the adoption of water-saving practices.

Although these BMPs categories were common across the study sites, their specific implementation details varied considerably, reflecting the need for customization by local actors.

The results indicate that the BMPs that are expected to bring improvements to each site are related with current conditions. In Egypt, where limited water resources are a concern, the best-performing BMP was a WUA intervention designed to decrease water use (drip irrigation); while in Kenya and Sudan, where water resources are mostly limited by distribution, the best-performing BMPs were also WUA interventions, but designed to increase water availability. In contrast, Agroforestry BMPs were found to perform the best as they provide improvements for crops and soils which match the concerns of local managers. The assessment also highlighted how BMPs with low performance might be improved with technical changes.

# 1. Introduction

## 1.1. Background

The WATDEV project has developed locally adapted Best Management Practice (BMP) scenarios for irrigated agriculture in Egypt, Ethiopia, Kenya and Sudan. The process began during the first regional workshop in 2023, where local stakeholders identified and selected several BMPs (deliverable D1.3.1). Subsequently, local workshops were developed with farmers to define the specific characteristics of each BMP, including crop types, and implementation location. In parallel, regional workshops were conducted with managers and other decision-makers to identify BMP implementation scenarios that would be most relevant for further assessment within the project (deliverable D3.1.2).

Concurrently, a modelling toolbox was developed to support the assessment of these BMP scenarios using a set of environmental and socioeconomic Key Performance Indicators (KPIs). The WATDEV toolbox analyses outputs from the WATDEV integrated model, which is based on a modified SWAT model coupled with MODFLOW and DSSAT models to enable detailed assessment of groundwater dynamics and crop growth where required (deliverable D3.1.1). The toolbox combines these biophysical model outputs with a socio-economic assessment based on economic assumptions and applied a Multi-Criteria Analysis (MCA) to evaluate the performance of each BMP relative to present-day conditions from multiple stakeholder perspectives (deliverables D4.1.2, D4.2.1 and D4.3.1).

Under the Activity A3.1, the BMP scenarios were adapted parameterised to meet the requirements of the WATDEV modelling framework. An initial round of simulation then conducted generating preliminary results for each study area and BMP scenario (see deliverable D3.1.2b).These results, together with a preliminary socio-economic analysis, were presented to regional stakeholders and local farmers during workshops held in November and December 2025 in each study area (except in Sudan, where, due to the political situation, the workshops were held online). During these sections, participants were asked to validate both the model application and BMP design, and to propose any adjustments needed to better reflect local conditions and improve realism. Regional stakeholders were also invited to provide a preliminary interpretation of model results for each BMP across the selected KPIs, and to assign weights reflecting the relative importance of each KPI when assessing overall BMP performance using a MCA.

Following the workshops, the models and BMP scenarios were revised in line with stakeholder feedback wherever technically feasible. The updated configurations were then re-run and the KPIs were recalculated using the revised biophysical and socio-economic parameters. Local water managers and experts were again asked to validate the underlying assumptions during regional training events held in February 2026 in Europe, and in May 2026 in Ethiopia and Egypt.

Each BMP scenario was evaluated across both technical and socio-economical KPIs, and aggregated scores summarizing all KPIs were calculated using a MCA. Multiple aggregated scores were calculated to reflect different optimization objectives, including overall system development, farm-level development, food security, water scarcity, and environmental protection. For each objective, KPIs were weighted differently based on the information collected during the regional workshops. The aggregated score for each BMP scenario was then compared with a similar calculation made for the present-day (baseline) conditions to assess the extent to which scenarios improve – or do not improve – the performance of the system under each optimization objective.

Originally, the results of these activities were planned to be presented in two separate deliverables: D3.2.1 (BMPs scenarios modelled), which would describe the methodological details of the assessment approach, and D3.2.2 (Final set of intervention scenarios), which would present the main results. This combined deliverable integrates D3.2.1 and D3.2.2 into a single consolidated document: Section 2 provides an overview of the approaches and key results (D3.2.2), while Sections 3, 4, 5 and 6 present detailed analyses for each study area (D3.2.1).

## 1.2. Objectives

The overall objective of this work was to use the integrated model to assess the overall performance of selected BMP scenarios based on a range of KPIs. The specific objectives were to:

- apply the WATDEV integrated model to simulate BMP scenarios validated by regional stakeholders and local farmers in each study site;
- provide results per each BMP scenario in terms of environmental KPIs directly simulated by the model, and socio-economic KPIs, derived through post-processing in the WATDEV Toolbox;
- compare the aggregated sociotechnical performance of different BMP scenarios using MCA across multiple management objectives.

# 2. Assessment of BMP intervention scenarios

## 2.1. BMP scenarios

The WATDEV integrated model was applied to case studies in each of the project's target countries:

- Sharqia governorate in Egypt;
- The Koga dam in Ethiopia, including both the irrigation command area and the watershed upstream of the dam;
- The Hola and Bura irrigation schemes in Kenya, with the model simulating the entireTana River Basin;
- The Gezira irrigation scheme in Sudan.

**Table 1** – Summary of the Best Management Practices tested in the four study areas.

| Study area | | Cultivation changes | Agroforestry | Water Users' Association |
|---|---|---|---|---|
| Sharqia (Egypt) | | • Composting, with Drip irrigation | • Intercropping: citrus trees with soybeans or eggplants, with Drip irrigation | • Drip irrigation (+ improved flood irrigation for rice)<br>• Conjunctive water use: surface and groundwater, with Drip irrigation |
| Koga (Ethiopia) | Command Area | • Crop Rotation: 3-year crop rotation w/ double cropping | • Agroforestry: avocado trees with seasonal crops | • Conjunctive groundwater use: with reservoir water, and Crop Rotation CA |
| | Upstream Catchment | • Crop Rotation: 3-year crop rotation | • Eucalyptus: woodlots in upstream catchment areas with high slopes<br>• Forage grass: similar to Eucalyptus, with permanent grass | N/A |
| Hola/Bura (Kenya) | | N/A | • Agroforestry: mango cultivation and hedgerows around annual crops<br>• Agroforestry plus WUA BMP | • Water Use Association: increased water supply and field levelling |
| Gezira (Sudan) | | N/A | N/A | • WUA A: earlier access to water and planting<br>• WUA B: WUA A BMP with increased water supply |

The model was used to assess a range of BMP scenarios identified by local stakeholders and subsequently refined to align with the capabilities and requirement of the WATDEV modelling framework. These scenarios are summarised in Table 1. The selected BMPs can be grouped of three broad categories:

- <u>Cultivation changes</u>, including changes to crops and rotations, cropping calendars, and/or to fertilization application;

- Agroforestry interventions, involving the introduction or expansion of shrub crops and fruit trees, in some cases intercropped with annual crops;
- Water users' association (WUA) interventions, aiming at improving water distribution, and irrigation management on farm level.

However, the specific design and implementation details of these BMP categories vary across the study areas, reflecting local agricultural practices and stakeholder preferences, as illustrated in the table 1. This was particularly evident for water management intervention, which were closely linked to the characteristics of existing irrigation infrastructure in each location. In addition, several BMP sceneries combined measures from more than one category. For example, in Egypt, the adoption of drip irrigation was evaluated both as a standalone BMP and as a component integrated into all other BMP scenarios.

The spatial extent of BMP implementation also varied among the study areas:

- Sharqia (Egypt): the intercropping BMP was applied only in areas characterised by sandy soils; whereas all other BMPs were implemented across the entire study area.
- Koga (Ethiopia): most scenarios were distinguished between the irrigation command area and the upstream catchment of the Koga Dam. The Agroforestry Command Area BMP was applied only in irrigation blocks with relatively low annual crop yield.
- Hola and Bura (Kenya): the Agroforestry BMP was represented as an expansion of the irrigated area; while all other scenarios were applied across the entire study area.
- Gezira (Sudan): all BMPs were implemented throughout the entire study area.

These differences in spatial implementation reflect the diverse biophysical, infrastructural, and management conditions across the four case studies, as well as stakeholder preferences regarding the most appropriate locations for BMP adoption.

Model results were produced for the Key Performance Indicators (KPIs) described in the next section. As the WATDEV modelling framework is primarily based on the SWAT model, most KPIs were derived from SWAT outputs (Arnold et al., 2012).

## 2.2. Assessment approach

A Multiple Criteria Analysis (MCA) was conducted to compare the performance of different BMP scenarios against the baseline (present-day) conditions. MCA is a decision-support method used to evaluate alternative options based on multiple socio-technical performance indicators (e.g. technical, environmental, socio-economic criteria) and development objectives (e.g. increasing crop production, improving resource-use efficiency, and maximizing economic benefits). MCA has been widely applied in the assessment and planning of agricultural land management (Gebre et al., 2021).

In this study, MCA was based the KPIs identified by local stakeholders and presented in Table 2. These indicators include:

- Biophysical KPIs, related to crop production, soil quality and water resources, which were derived directly from the outputs of the WATDEV model; and
- Socioeconomic KPIs, which were calculated through post-processing model outputs using a set of economic assumptions summarised in Table 3. The economic assumptions underpinning the socio-economic assessment were validated by local stakeholders during WATDEV Toolbox training workshops held in May 2026.

The KPIs were organised into four thematic groups: crop production, soil quality, water resources, and economic performance. During the regional stakeholder workshops held in November and December 2025, the managers assigned weights to each group and further distributed weights among the individual KPIs within each group.

**Table 2** – Key Performance Indicators (KPIs) used in assessing each BMP.

| Group | Key Performance Indicator |
|---|---|
| Crop | Crop yield<br>Fertilizer use efficiency (N, P)<br>Carbon sequestration in crop |
| Soil | Soil erosion<br>Soil fertility (organic Carbon, N, soluble P, organic P) |
| Water | Irrigation water use (total and efficiency)<br>Groundwater and surface water contamination by Nitrate |
| Economy | Benefit-cost and Price-cost ratio<br>Cost savings from BMP adoption<br>Net farm income<br>Economic water-use efficiency<br>Labour use<br>Community access to water |

**Table 3** – Economic Key Performance Indicators (KPIs) and economic assumptions used in the calculation.

| Economic KPIs | Definition | Economic assumptions |
|---|---|---|
| Benefit-cost ratio | Ratio between the discounted economic value of all benefits generated by implementing the BMP and the discounted costs to implement the BMP. | • Discount rate<br>• Lifetime of BMP<br>• Economic value of benefits of BMP<br>• Capital and Operational expenses of BMP |
| Price-cost Ratio | Ratio between the selling price and the cost of production for each agricultural product. | • Selling price for each product after BMP<br>• Cost of cultivation for each product after BMP |
| Cost savings from BMP adoption | Difference in cost of cultivation before and after the BMP implementation | • Cost of cultivation before and after the BMP |
| Total household Net farm income | Gross farm income minus total production costs & expenses | • Yields after BMP (model result)<br>• Selling price for each product after BMP<br>• Cost of cultivation of each product after BMP |
| Labour use | Sum of crop-specific labour requirement by their corresponding cultivated area | • Crop-specific labour requirement<br>• Cultivated area per crop |
| Community access to water | Number of community members with access to water rights or secure water resource allocations | • Total water use for agriculture (model result)<br>• Cultivated area. |
| Economic efficiency in water use: | Ratio between the monetary value of the agricultural output produced and the water used. | • Amount of water required per crop after BMP (model output)<br>• Yields after BMP (model output)<br>• selling price for each product after BMP |

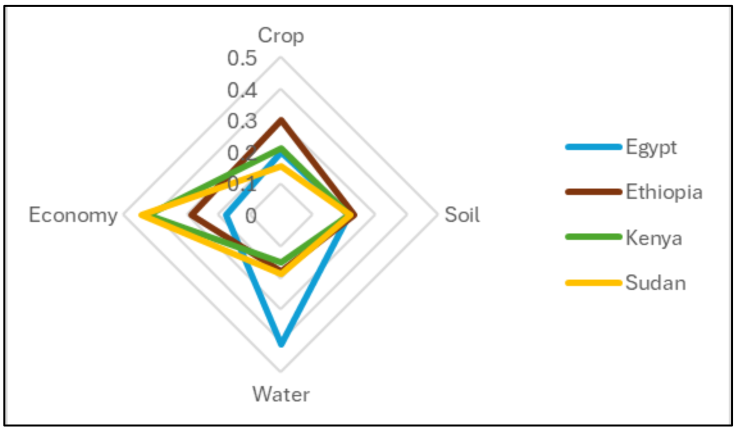



**Figure 1** – Weights assigned to each Key Performance Indicator group by regional managers of the WATDEV case study countries; in each country, the total sum of weights is 1.

Figure 1 compares the weighting schemes assigned by the managers from the four case study countries. Managers in Egypt placed the greatest emphasis on water resources indicators, whereas those in Ethiopia prioritised food production indicators, reflecting the particular challenges of water scarcity and food security in the respectively countries. In contrast, managers in Kenya and Sudan assigned relatively greater importance to economic performance indicators.

## 2.3. Assessment results

Table 4 presents the assessment results for each BMP across the study area. Several BMPs are not recommended for application based on the analysis. This does not imply that these BMPs do not lead to improvements in the KPIs; in most cases, the model simulates the improvements in crop production, soil conditions and water resources as expected by farmers and experts. It indicates that these improvements are not sufficient to offset the associated investment and operational costs required for their implementation, as indicated by an MCA score below baseline conditions. The BMP results can be summarised as follows:

- Sharqia (Egypt): Drip Irrigation was identified as the most effective BMP, as it reduced irrigation water use without decreasing crop yields. Other BMPs were considered as extensions of the Drip Irrigation; however, the additional benefits of these measures did not justify their extra investment and operational costs. In the case of Composting, these added costs outweighed the benefits, eliminating the overall advantage.
- Koga (Ethiopia) – Command Area: Agroforestry was assessed as the most beneficial BMP, primarily due to increased income from higher crop prices, despite higher water requirements. Crop Rotation also performed well, offering moderate benefits through lower costs, albeit fewer negative impacts. The addition of Conjunctive Groundwater Use to crop rotation provided only marginal benefits relative to its investment cost.
- Koga (Ethiopia) – Upstream Catchment: Eucalyptus plantations and, to a lesser extent, Forage Grass were assessed as beneficial BMPs, increasing net farmer income and reducing erosion, although eucalyptus use remains controversial among managers. Crop Rotation, however, was associated with lower farmer income and limited erosion benefits despite improved fertilizer-use efficiency.
- Hola and Bura (Kenya): the Water Use Association BMP improved the benefit-cost ratio with few limited negative aspects. Agroforestry delivered only modest improvements that did not compensate for implementation costs. The combined implementation of measures further reduced overall performance, as higher costs outweighed the benefits of WUA interventions.
- Gezira (Sudan): both Water User Association BMPs (A and B) resulted in higher crop yields and improved irrigation and fertilizer-use efficiency, with WUA B performing best overall. Although cost savings were limited, the results indicate a favourable balance between costs and benefits. WUA B also contributed to increased farmer income.

Overall, each system includes one or more BMPs that could enhance agricultural performance. In addition, BMPs that were not recommended for application still provide useful insights for improvement, either through refinements of the technical design or by accounting for co-benefits not included in the analysis. Important co-benefits not captured in the selected KPIs include:

- Cultivation changes: reduced dependency on mineral fertilizers and improved resilience to price fluctuations;
- Agroforestry: income diversification and provision of fodder;
- Water Users' Association: expansion of irrigated areas to new blocks, and improved reliability and reduced conflict through diversified water supply sources.

The analysis also does not capture certain potential negative aspects of the BMPs, such as the impacts of higher irrigation water use on the reliability of water supplies (even when efficiency improves), the potential implications for food security of replacing food crops, or the administrative challenges in associated with implementing more complex water management approaches.

The assessment results do not mean that the BMPs are not technically sound at the farm level. In fact, the simulations show that most BMPs achieved their intended objectives, whether in terms of increased yield, improved irrigation water availability and efficiency, or reduced soil erosion. Rather, the MCA results highlight that, for some BMPs, these farm-level benefits are insufficient to offset implementation and operational costs, or to compensate for broader trade-off such as increased water demand. However, these findings should be interpreted in light of additional co-benefits not included in the MCA, as well as under alternative economic assumptions that could reflect the relative performance of the BMPs

**Table 4** – Summary of Best Management Practice assessment results for the four study areas.

| **Study area** | | **Best Management Practice** | **Strengths** | **Weaknesses** |
|---|---|---|---|---|
| Sharqia (Egypt) | | Drip Irrigation | • Lower irrigation water use<br>• Higher technical and economic water-use efficiency | • Lower price-cost ratio |
| | | Composting<br>(plus Drip Irrigation)<br>***Not recommended by MCA*** | • Same as Drip Irrigation<br>• Higher net farm income | • Same as Drip Irrigation<br>• Lower fertilizer use efficiency<br>• Lower benefit-cost ratio |
| | | Intercropping<br>(plus Drip Irrigation) | • Same as Drip Irrigation | • Lower price-cost ratio than Drip Irrigation |
| | | Conjunctive Water Use<br>(plus Drip Irrigation) | • Same as Drip Irrigation | • Same as Drip Irrigation |
| Koga (Ethiopia) | Command Area | Crop Rotation | • Higher price-cost ratio | • Lower net farm income<br>• Lower fertilizer use efficiency |
| | | Agroforestry | • Higher price-cost ratio and net farm income | • Higher irrigation water use<br>• Lower technical and economic water use efficiency<br>• Lower fertilizer use efficiency |
| | | Conjunctive Groundwater Use<br>(plus Crop Rotation)<br>***Not recommended by MCA*** | • Same as Crop Rotation | • Same as Crop Rotation<br>• Lower benefit-cost ratio |
| | Upstream Catchment | Crop Rotation<br>***Not recommended by MCA*** | • Higher fertilizer use efficiency<br>• Lower labour use | • Lower crop yields<br>• Lower net farmer income<br>• Higher erosion |
| | | Eucalyptus | • Lower erosion<br>• Higher fertilizer use efficiency<br>• Higher net farmer income and price-cost ratio | • Controversial among managers |
| | | Forage grass | • Lower erosion<br>• Higher fertilizer use efficiency<br>• Higher net farmer income | • Lower price-cost ratio |
| Hola/Bura (Kenya) | | Agroforestry<br>***Not recommended by MCA*** | • Lower erosion | • No cost savings |
| | | Water Use Association | • Good benefit-cost ratio | • No cost savings |
| | | Agroforestry plus WUA<br>***Not recommended by MCA*** | • Good benefit-cost ratio<br>• Lower erosion<br>• Higher Nitrogen use efficiency | • Lower price-cost ratio and net farmer income<br>• Lower technical and economic water use efficiency |
| Gezira (Sudan) | | Water Users Association A | • Higher crop yield, irrigation use efficiency, and fertilizer use efficiency<br>• Good benefit-cost ratio | • No cost savings |
| | | Water Users Association B | • Same as WUA A, but with better improvement levels<br>• Higher net farmer income<br>• Lower water contamination with nitrate | • No cost savings |

# 3. Detailed assessment for Sharqia governorate, Egypt

## 3.1. Model application

The model was applied to the irrigated areas of Sharqia governorate in the Nile Delta, covering approximately 3870 km$^2$ of irrigated land (Figure 2). The model simulates only agricultural fields, while water sources are represented in a simplified manner. A more detailed application that explicitly incorporates the canals and aquifer system is currently under way.

Each sub-basin in Figure 2 represents an irrigated block supplied by a specific irrigation canal. The figure also illustrates the canal network and connections between individual canals and the corresponding sub-basins.

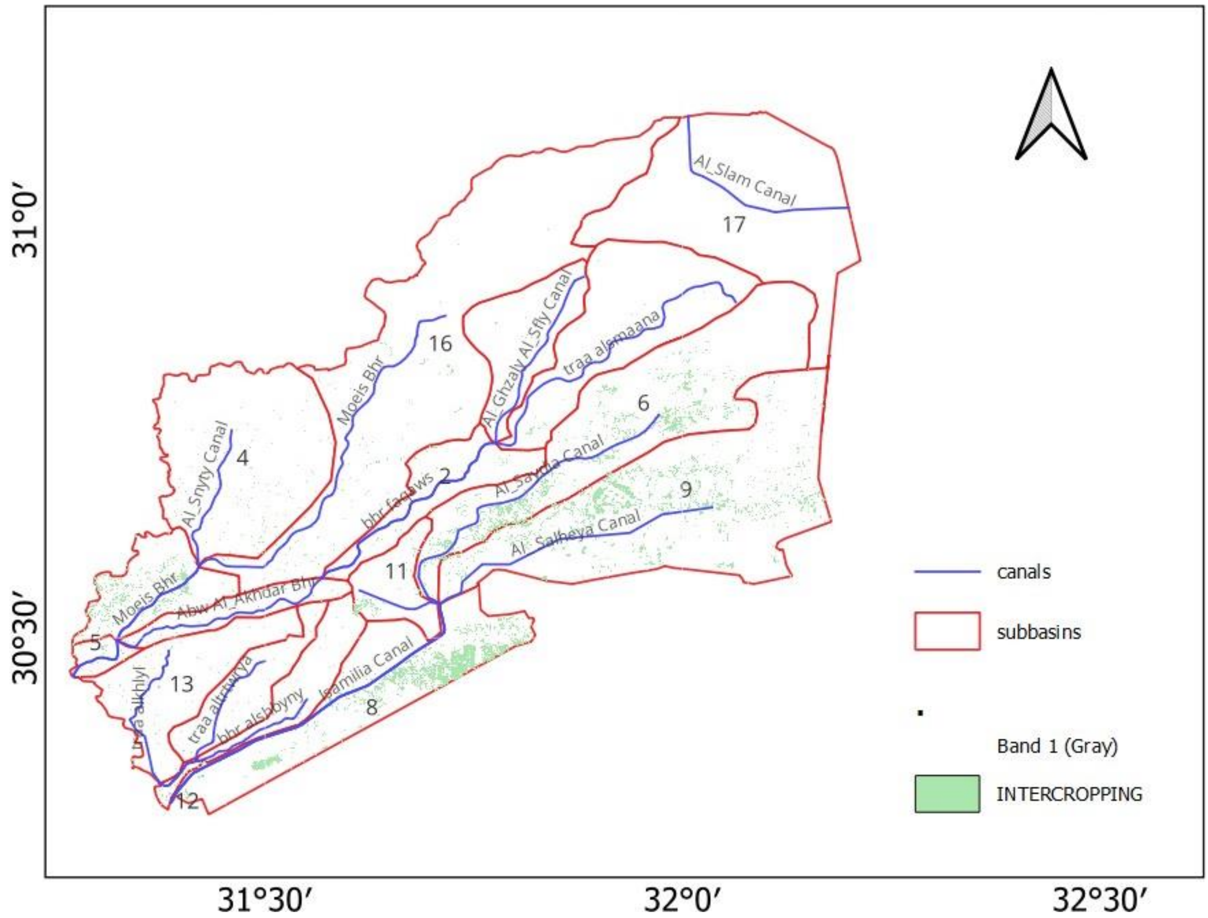



**Figure 2** – Map of the Sharqia study area, including the simulated sub-basins (in this case, irrigation blocks), irrigation canals, and proposed zones for intercropping implementation.

The model was run over a 31-year period to simulate present-day conditions, reflecting current farming practices in Sharqia. Farmers typically cultivate two crops per year, following one of three dominant double-cropping systems consisting of a winter and a summer crop: wheat-corn, rice-clover, and wheat-tomato (Figure 3). A smaller proportion of the agricultural area is dedicated to orange orchards.

Chemical fertilizers are commonly applied. Urea serves as the primary source of nitrogen fertilization, while NPK fertilizers provide supplementary nitrogen and phosphorus through the growing season.

At present, most farmers in the study area mostly use traditional surface (furrow) irrigation method, although drip irrigation has been adopted in other parts of the Nile Delta. Distribution canals constitute the main water source for irrigation. However, farmers located further downstream along the canal branches may experience reduced water availability, as canal water does not always reach the tail ends of the distribution network.

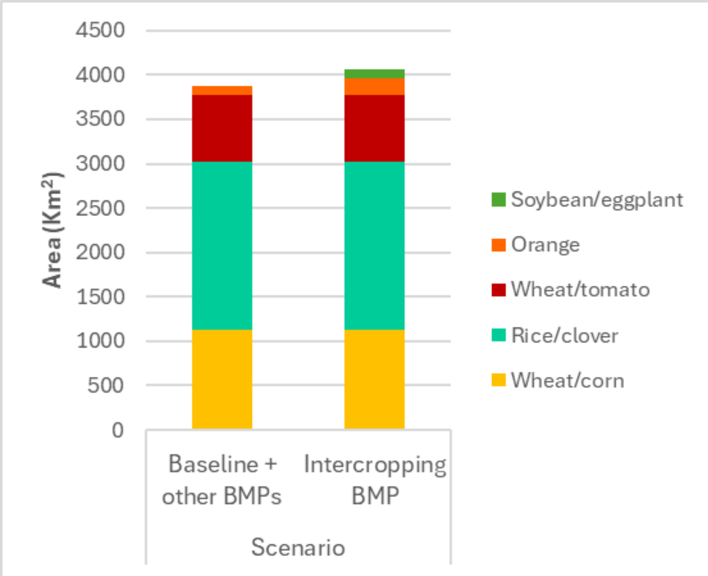



**Figure 3** – Crops considered in the Sharqia model and respective areas.

Simulated crop yields were calibrated against observed values reported in the literature, resulting in generally good agreement (Figure 4). The overall average error was 1.2%, although performance varied considerably among crops. The relatively poor performance for orange trees is likely attributable to uncertainties in fruit water content. Model outputs are expressed in dry biomass, whereas reported yields are typically given as fresh weight. To enable comparison, simulated yields must therefore be converted from dry to fresh weight using a crop-specific water content factor. Because this factor can vary substantially, it can strongly influence the results, particularly for crops with high water content, such as oranges.

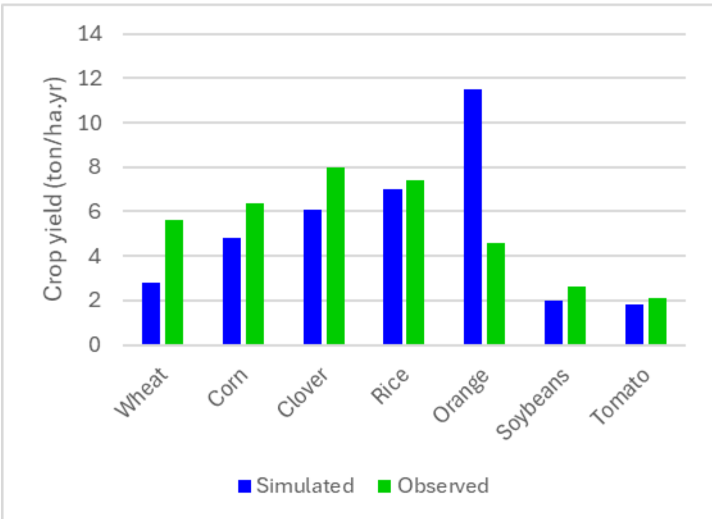



**Figure 4** – Model performance for total crop yield in Sharqia.

## 3.2. BMP scenarios

The following BMPs were selected for simulation in the Sharqia study area. Drip irrigation was considered the core BMP; while all other BMPs were evaluated in combination with drip irrigation.

- Drip Irrigation: improve irrigation water-use efficiency through the adoption of drip irrigation systems. For rice paddies, equivalent water-saving irrigation measures were considered.
- Composting: in combination with drip irrigation, partially replace chemical fertilizers with composted manure, to enhance soil water retention, improve soil properties, and increase nutrient availability.
- Intercropping: in combination with drip irrigation, integrate annual crops (soybeans and eggplants) with citrus trees to increase food production and crop diversity; this measure was applied only to the areas with light sandy soils.
- Conjunctive water use: in combination with drip irrigation, utilise both surface water and groundwater sources to improve water allocation and enhance irrigation reliability among farmers.

### Drip Irrigation

This BMP was designed promote more efficient irrigation practices in the study area with the objective of improving water-use efficiency. The measure was represented as a transition from traditional flood irrigation to drip irrigation system. For flooded rice cultivation, alternative water-saving management practices were considered: field levelling to reduce ponding, and improved bund management to minimize losses through leakage.

**Figure 5** – Drip irrigation in Sharqia (photo by Samar Gomaa).

### Composting

Local stakeholders selected compost as an organic fertilizer to increase soil organic matter (SOM), thereby improving soil water-holding capacity and enhancing nutrient availability for crops. The BMP is conceptualized as the application of compost to the soil prior to tillage. The compost consists of a mixture of plant residuals, ash and organic matter derived from animal waste. It is commercially available and can also be produced by farmers in accordance with regulations established by the Egyptian Ministry of Agriculture and Land Reclamation (MALR). This was evaluated in combination with drip irrigation.

Composting practices have already been introduced in Sharqia Governorate. An example is the SEKEM farm in the Bilbeis district, located in the southern part of the study area. At SEKEM, compost is produced from organic waste materials, including plant residues and animal manure from cows, sheep, and pigeons (Figure 6) (SEKEM, 2025). The organic compost used in the study area combines animal-derived organic waste with plant ash and contains essential nutrients such as nitrogen (N), phosphorous (P) and potassium (K), which enhance soil fertility. A well-balanced compost mixture typically includes carbon-rich ("brown") materials, nitrogen-rich ("greens") materials, adequate moisture, and sufficient aeration to support the decomposition process (US EPA, 2025).

For the modelling exercise, the compost was assumed to contain 0.5% N and 0.2% P. Compost application was simulated for all major crops in the study area: including maize, wheat, rice, clover, tomato, soybeans and orange trees. A fixed amount of compost was applied approximately two weeks before sowing. Any additional nutrient requirements were supplied through chemical fertilizers following usual fertilization schedule. In the model, these supplementary applications were simulated based on plant nutrient stress, rather than prescribed fixed application rates.

**Figure 6** – Composting in SEKEM farm (SEKEM, 2022).

### Intercropping

This BMP was defined by local actors as the integration of permanent and annual crops, in this case combining citrus trees with a soybean and eggplant crop rotation. The objective of intercropping is to increase food production and crop diversity, while enhancing ecosystem services. The presence of trees can improve soil water retention whereas soybean, as a leguminous crop, contribute to biological nitrogen fixation and can improve soil fertility. In addition, the shade provided by trees may create more favourable microclimatic conditions for the associated crops. However, this potential benefit could not be explicitly represented in the WATDEV integrated model.

Within the study area, intercropping was implemented only on fields with sandy soil (Figure 2). As a result, the measure increased the overall cropped area (Figure 3). The intercropping BMP was evaluated in combination with drip irrigation.

### Conjunctive water use

This BMP was defined as the combined use of groundwater and surface water to improve spatial distribution of irrigation water, particularly for farmers located farther downstream along canal branches. It is conceptualized as the use of groundwater to supplement canal water during dry periods. In the model, conjunctive water use is represented as a proportion of total irrigation water applied to crops, ranging between 10% and 20%. This BMP is evaluated in combination with drip irrigation.

**Figure 7** – Groundwater production well for irrigation in Sharqia (photos by Samar Gomaa).

## 3.3. BMP assessment

Results from the implementation of the BMPs are shown in Figure 8 for crop yield and irrigation water use; and are further disaggregated by crop in Figure 9. Spatial variability is not shown, as differences were primarily driven by variations in crop types rather than spatial heterogeneity.

Overall, drip irrigation did not lead to changes in crop yield, even when combined with conjunctive water use. This is because, according to the model results, none of the crops currently experiences water or nutrient stresses. Drip irrigation combined with composting led to a slight decrease in crop yields, mainly affecting clover. Similarly, the combination of drip Irrigation and Intercropping resulted in marginal lower yields; however, this effect is primarily attributable to changes in the crop composition rather than reduced performance of individual crops. In particular, citrus trees exhibit lower yields than the annual crops they replace. This does not necessarily indicate reduced system performance, as citrus production may provide other benefits such as higher market prices and increased farm diversification.

In contrast, drip irrigation led to substantial reduction in irrigation water use across all scenarios, with a corresponding increase in water-use efficiency. This represents a clear improvement over current conditions. Additional reduction in water use was observed when drop irrigation was combined with composting, due to improved soil water-holding capacity (particularly for citrus trees and maize); and with Intercropping, due to the lower water requirements of soybeans. However, these additional gains are relatively small compared with the effect of drip irrigation alone.

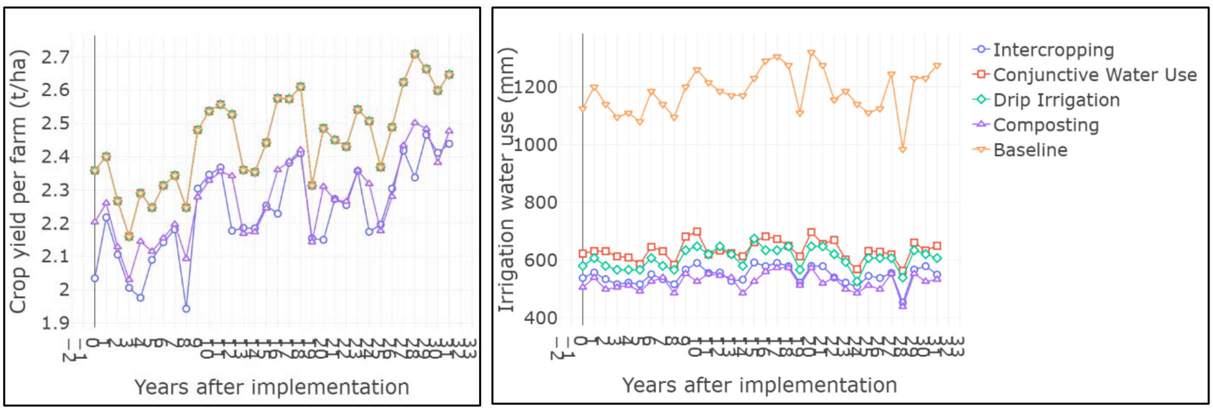



**Figure 8** – Annual crop yield (dry weight, left) and irrigation water use (right) since implementation (average across all crops) for all Best Management Practices in the center of Sharqia (subbasin 2 – see Figure 2), compared with present-day (Baseline) conditions.

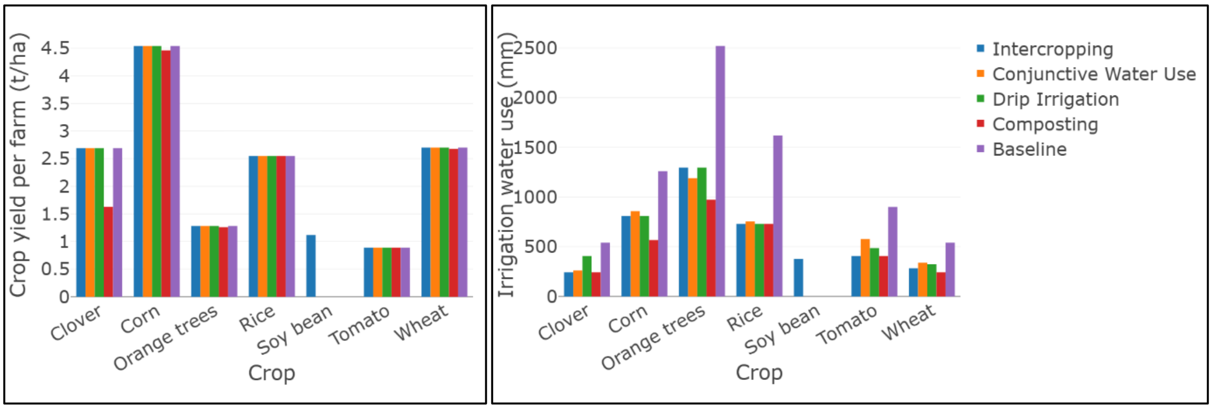



**Figure 9 –** Annual crop yield (dry weight, left) and irrigation water use (right) for the middle of the time series, per crop, for all Best Management Practices in the center of Sharqia (subbasin 2 – see Figure 2), compared with present-day (Baseline) conditions.

Figure 10 shows the score of each BMP across the selected KPIs, while Figure 11 presents the results of Multi-Criteria Analysis (MCA). The analysis indicates that all BMPs are expected to outperform the baseline scenarios, with the exception of the composting scenario. The highest-performing options are drip irrigation alone and drop irrigation combined with conjunctive water use. Both measures substantially reduce irrigation water consumption, leading to significant improvement in technical and economic water-use efficiency. The main drawback identified is a lower price-cost ratio. In addition, conjunctive water use may contribute to more equitable distribution of irrigation water among farmers, a benefit that was not adequately captured by the model. The addition of Intercropping to drop irrigation does not provide a clear improvement relative to its additional cost. However, the MCA did not account for the potential benefits of diversified farmers' income sources, which could increase the attractiveness of this option for farmers.

The combination of composting and drip irrigation generates modest increases in net farm income, but these gains are offset by lower fertilizer-use efficiency — particularly for rice and wheat — and less favourable benefit-cost ratio. As a result, the advantages largely negate the benefits associated with drip irrigation. Nevertheless, the MCA did not account for potential disruptions in mineral fertilizer supplies or sharp increases in fertilizer prices, such as those experienced during recent geopolitical intensions in the Middle East. Under such circumstances, locally-produced compost could become a more attractive alternative. Furthermore, the performance of this BMP could potentially be improved by reducing mineral fertilizer application rate for wheat and rice, therefore increasing fertilizer-use efficiency and lowering input costs.

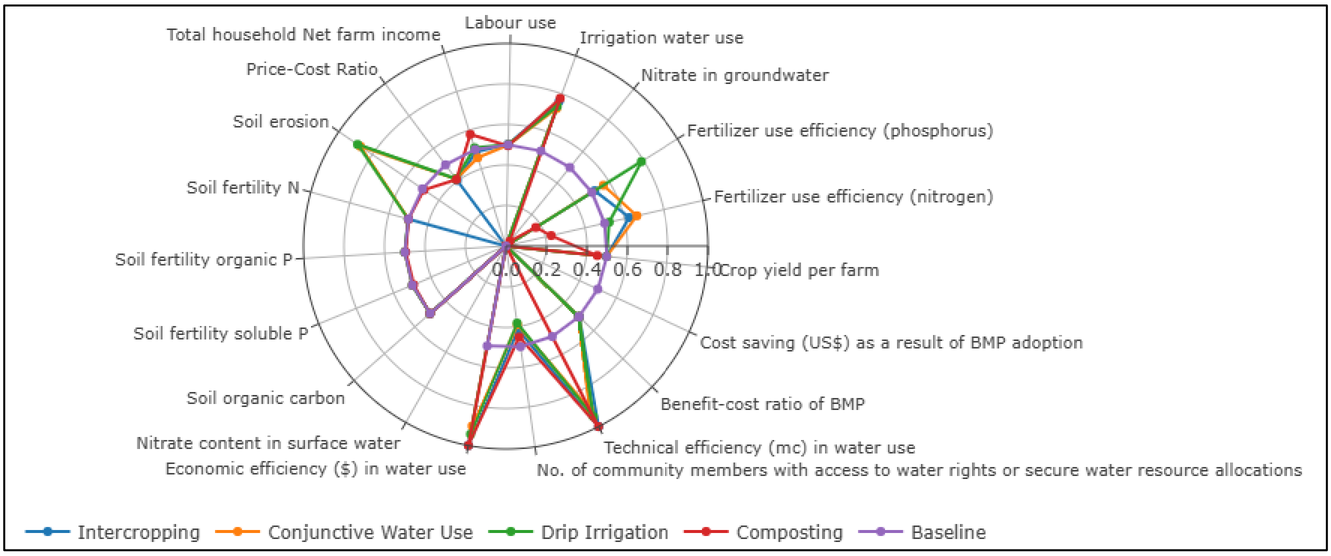



**Figure 10** – Scoring of Key Performance Indicators for Sharqia, for the Baseline and all Best Management Practices; scores rank from 0 (worst) to 1 (best), with Baseline scoring 0.5 except when there is no data.

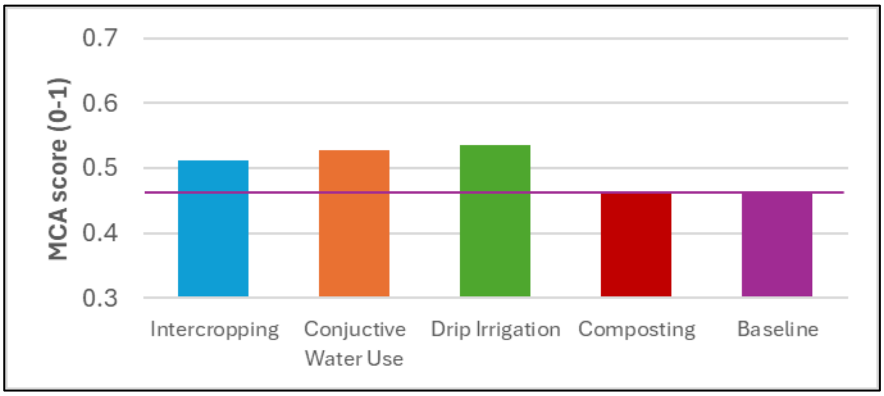



**Figure 11** – Multi-Criteria Analysis score for the Baseline and all Best Management Practices for Sharqia, calculated from weighted Key Performance Indicators.

# 4. Detailed assessment for the Koga command area and watershed, Ethiopia

## 4.1. Model application

The model was applied to the entire Koga study area (Figure 12), divided into two distinct regions:

- The Koga Command Area, located downstream of the Koga reservoir, comprising approximately 70 km$^2$ of irrigated agricultural land area (Figure 13); and
- The Upstream Catchment, draining into the Koga reservoir, comprising about 150 Km$^2$ of predominantly rainfed agricultural land.

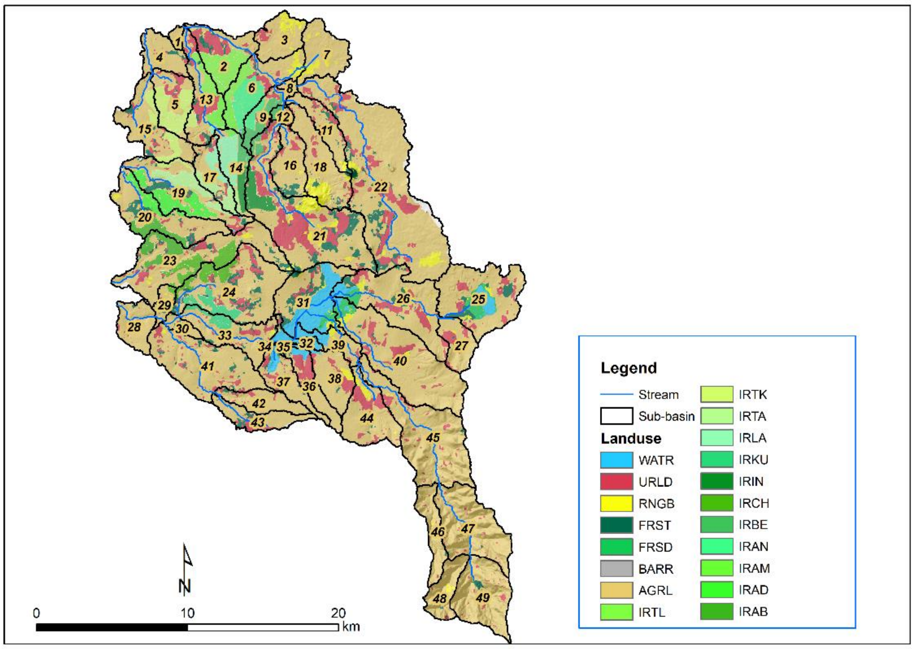



**Figure 12 –** Map of the Koga study area, showing the simulated sub-basins in the command and upstream areas, respectively North and South from the reservoir (shown in blue).

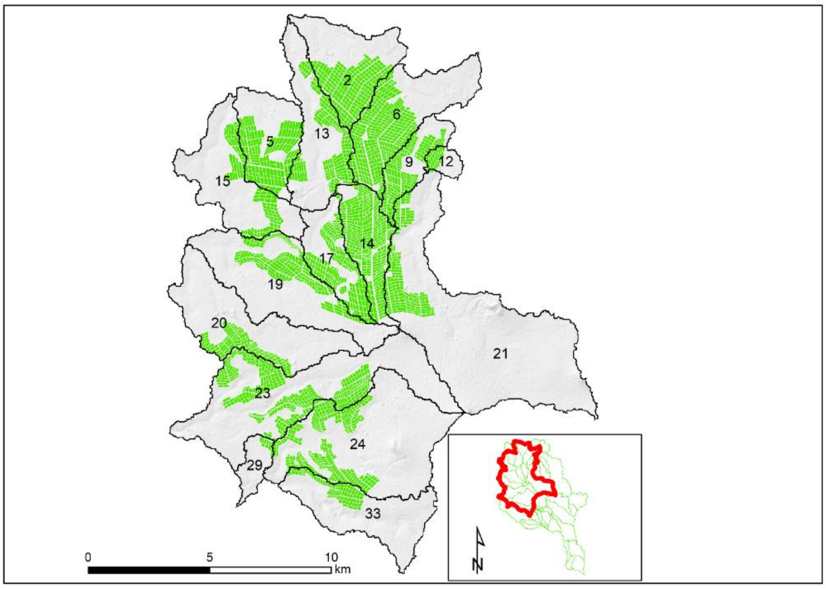


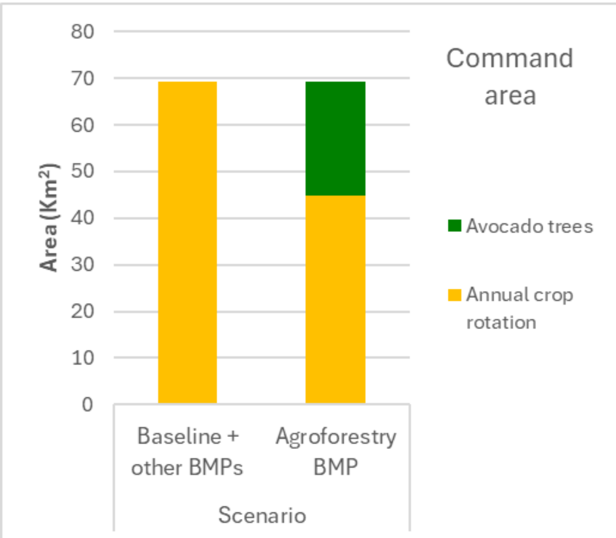

**Figure 13 –** Detailed map of the Koga command area, with the green areas representing irrigation blocks.

A fully integrated system model was developed for the study area, explicitly representing agricultural fields, the stream network, groundwater resources, and the Koga reservoir. This integrated approach enabled the assessment of interactions between land use, agricultural production, water resources, and reservoir dynamics across the entire watershed.

The model was run over a 13-year period to simulate present-day conditions in the Koga study area. Due to land scarcity, crop production is dominated by cereal-cereal and cereal-vegetable rotation, with limited inclusion of legumes.

Within the command area, farmers typically practice double cropping, cultivating rainfed maize during the main rainy season followed by irrigated wheat during the dry season. According to the Koga Irrigation Development Office (as confirmed by Tegegne et al., 2025), the maize-wheat rotation is the dominant cropping system, covering approximately 70% of the command area (Figure **14** left). Farmers also cultivate minor crops including irrigated potatoes, maize, and perennial crops, but these were not represented in the model due to their limited spatial extent. In the upstream catchment, farmers mostly plant rainfed Teff (Figure **14** right). Other crops such as maize, occupy relatively small areas and were therefore excluded in the modelling exercise.

The actual crop water consumption within the Koga irrigation scheme is substantially lower than the volume of water released from the reservoir (Tegegne et al., 2025). This discrepancy is largely attributed to inefficient furrow irrigation practices (Asmamaw et al., 2021), and unregulated water abstraction by farmers, both of which contribute to significant water losses, and exacerbate water shortages within the irrigation system.



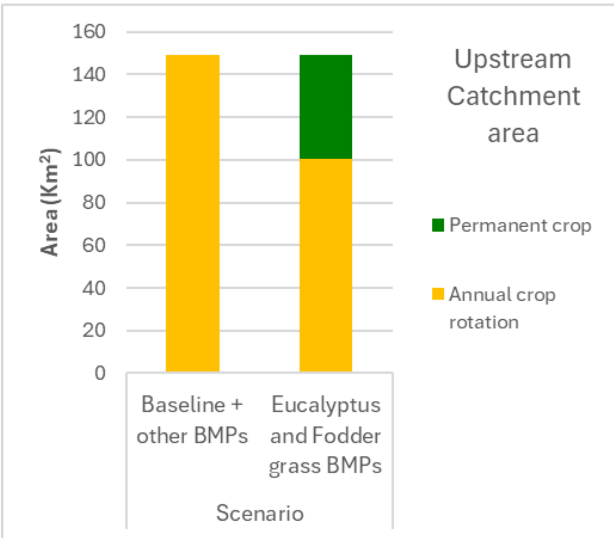




**Figure 14** – Crops considered in the Koga model for the Command Area (left) and Upstream Catchment (right), and respective areas.

Model calibration focused on streamflow, sediment yield, and crop yield. Simulated streamflow and sediment yield were compared against observation from the Koga River prior to the dam construction, representing water and sediment inflows from the upstream catchment. Model performance was satisfactory, with an average error of -2.1% for streamflow and -0.7% for sediment yield. Split-sample validation resulted in average errors of 3.3% for streamflow and -17.6% for sediment yield, indicating an acceptable representation of watershed hydrological and sediment dynamics.

Simulated crop yields were generally in good agreement with observed data obtained from the Koga Irrigation Development Office and the North Mecha District Agriculture Office, with an overall average error of 3.9% (Figure 15). However, model performance varied considerably among crops. The relatively poor performance for avocado yield is likely attributable to uncertainties in fruit water content. Model outputs are expressed as dry biomass, whereas reported yields are typically provided as fresh weight. To facilitate comparison, simulated yields must therefore be converted from dry to fresh weight using a crop-specific water content factor. Because this factor can vary substantially, it may strongly influence the results, particularly for crops with high water content, such as fruits.

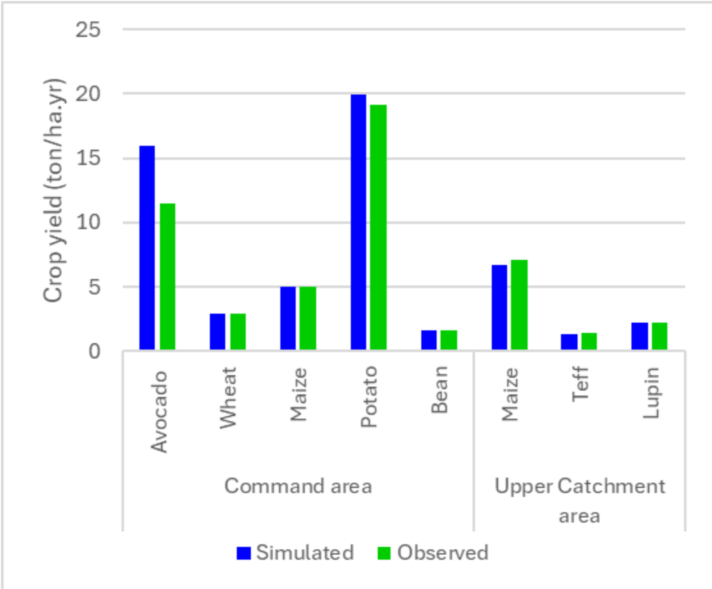



**Figure 15** – Model performance for crop yield in Koga.

## 4.2. BMP scenarios

In the Koga study area, the following BMPs were selected for simulation in the command area:

- Crop rotation in the Command Area: a 3-year rotation cycle with double cropping, including one rainfed and one irrigated crop per year. The system consists of two years of production (rainfed maize followed irrigated wheat or potato) and one year of regeneration (rainfed wheat followed by irrigated beans).
- Agroforestry in the Command Area: Cultivation of avocado in irrigation blocks with permeable soils, intercropped with cereals, to diversify food production systems.
- Conjunctive Groundwater Use: an improvement of the crop rotation BMP, this measure improves irrigation water allocation within the system through the combined use of surface water and groundwater sources.

The following BMPs were selected for simulation in the catchment upstream of the Koga Dam:

- Crop Rotation in the Upstream Catchment: a 3-year rotation cycle comprising two years of production (teff and maize) followed by one year of regeneration (lupin).
- Eucalyptus Plantation: tree plantations established in erosion-prone areas upstream of the Koga Dam to support livelihood diversification, with soil erosion control as co-benefit.
- Forage Grass: grass plantations established in erosion-prone areas upstream of the Koga Dam, primarily aimed at reducing soil erosion.

### Crop Rotation in the Command Area

Local stakeholders defined improved crop rotation systems for the command area with the aim of enhancing soil fertility and diversifying agricultural production. Particularly, emphasis was placed on moving beyond the prevailing market-driven practice of continuous cereal-based cropping systems by incorporating leguminous crops into the rotation schemes.

In consultation with experts from the North Mecha District Agriculture Office, a three-year crop rotation strategy was developed. The system combines two crops per year: one grow during the rainy season under rainfed conditions and one grow during the dry season under irrigation.

The rotation is structured as follows:

- First year: irrigated wheat (dry season) and rainfed maize (rainy season);
- Second year: irrigated potatoes (dry season) and rainfed maize (rainy season);
- Third year: irrigated wheat (dry season) and rainfed common bean (rainy season).

### Agroforestry in the Command Area

The local stakeholders considered a conversion of several irrigation blocks to avocado production as a strategy to diversify crop production. This BMP was implemented through intercropping avocado trees with seasonal crops in irrigation blocks characterised by soils with high saturated hydraulic conductivity and moderate clay content (Figure 16). These soil properties are favourable for both water movement and root development, thereby reducing the risk of root rot. This agroforestry practice covered 35% of the total command area (Figure 14 left). However, the intercropping of trees and seasonal crops was not simulated explicitly in the model due to limitations in simulating the effect of tree shading on understory crop growth within the integrated modelling framework.

**Figure 16** – Avocado tree intercropping in the Koga command area.

### Conjunctive Groundwater Use

This scenario addresses challenges associated with inefficient irrigation practices arising from crop clustering, as well as stakeholders' interest in equitable water allocation. It builds on the crop rotation BMP by incorporating crop clustering across all irrigation blocks and integrating conjunctive water use in line with the stakeholder' priorities.

Crop clustering aligns with Ethiopian government policies promoting agriculture modernization, as it strategically consolidates smallholder farmlands into contiguous mono-crop zones (Zeleke and Wordofa, 2024). This allows irrigation blocks to be managed according to relatively uniform crop water requirements. While it can improve agricultural and irrigation management efficiency, it may also increase irrigation demand during critical crop growth stages.

Model simulations indicate that the mid-season stages of cereals and vegetables represent periods of water stress, during which even minor water deficits can lead to substantial yield reductions (Chen et al., 2018). To address this, conjunctive use of shallow groundwater in combination with the Koga reservoir was proposed to supplement surface water supply during peak demand periods. Over the entire irrigation season, groundwater contributes a small share of water (2-3%), while the reservoir remains the dominant source (~97%).

### Crop Rotation in the Upstream Catchment

The crop rotation scenario for the upstream catchment follows the same rationale as the crop rotation BMP defined for the command area. In consultation with the North Mecha District Office of Agriculture (DOA), a simplified three-year crop rotation was developed that incorporates leguminous crops to improve soil fertility. Given that the upstream catchment is not irrigated, only one single crop per year was considered, cultivated under rainfed conditions during the rainy season.

The rotation is structured as follows:

- First year: teff
- Second year: maize
- Third year: lupin

### Eucalyptus Plantation

Regional stakeholders also considered Eucalyptus tree plantations in upstream of the Koga Dam to support livelihood diversification, with soil erosion control considered a potential co-benefit. Eucalyptus was selected due to its low input requirement and perceived economic advantages, although its effectiveness for soil conservation remains debated , particularly given potential soil disturbance with harvesting and logging activities.

In this BMP, eucalyptus plantation was implemented as dedicated woodlots. Crop production on the steepest slopes (greater than 15%; Figure 17) was replaced by eucalyptus plantation, affecting nearly 8.4% of the watershed area (Figure 14, right). Regular biomass harvesting by farmers was accounted for in the model, including its implications for the long-term soil conservation benefits provided by the tree cover. These woodlots are intended to provide an additional income source and contribute to livelihood diversification for local farmers.

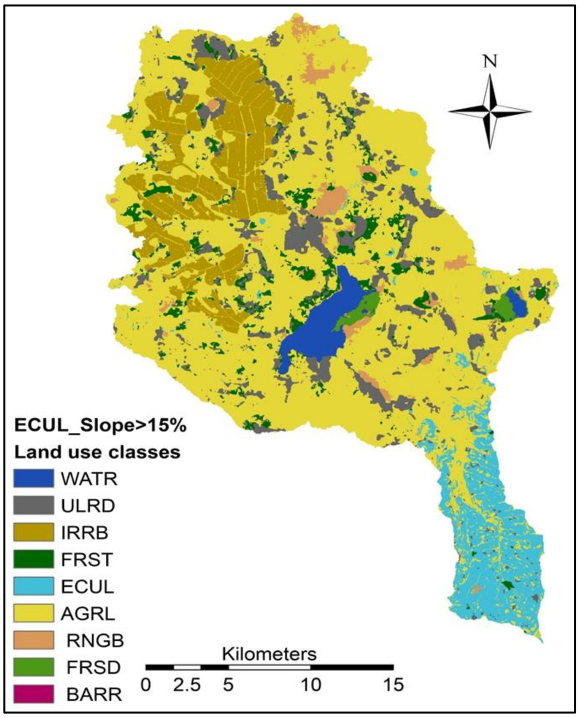



**Figure 17** – Land-use map of the Koga area showing upstream areas converted to eucalyptus woodlots.

### Forage grass

While local farmers expressed strong support for eucalyptus plantation because of their economic value, regional stakeholders raised concerns about the effectiveness of eucalyptus in controlling soil erosion. To address these concerns, they proposed the establishment of forage grasses in the same erosion-prone areas as an alternative BMP focused specifically on soil conservation. Forage grasses were considered potentially more effective for this due to their dense ground cover and extensive root systems, which help stabilize the soil and reduce surface runoff. In the model, forage grasses were implemented in the same areas identified for eucalyptus plantations on steep, erosion-prone slopes. Although forage grasses are perennial crops, they require replanting approximately every five years to maintain productivity and ensure continued effectiveness in erosion control.

## 4.3. BMP assessment

### Koga Command Area

The model indicates notable differences in crop performance across the command area under present-day condition. Irrigation blocks in the western part of scheme generally exhibit lower crop yields and higher irrigation water use than those in the eastern blocks (Figure 18). These differences are primarily attributable to variations in crop composition and soil characteristics between the two areas. Despite the baseline differences, the relative impacts of BMP implementation were broadly similar across the command areas. Therefore, only the results for the eastern section, which exhibits better overall performance are shown. Figure 19 shows the impacts of the BMPs on crop yield and irrigation water use in the Koga command area. Results for irrigated wheat are shown separately in Figure 20, and disaggregated in Figure 21.

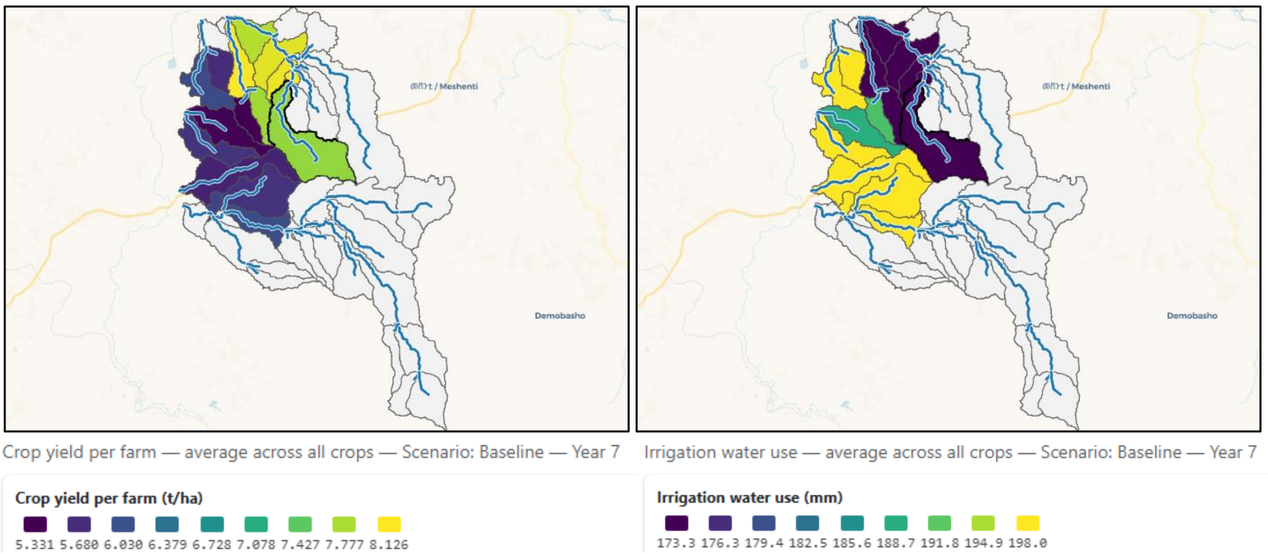



**Figure 18**– Annual crop yield (dry weight, left) and irrigation water use (right) in the mid period of the Koga command area (average across all crops) for present-day (Baseline) conditions.

Overall, Crop Rotation led to slightly lower average yields and reduced irrigation water use, both when implemented alone and in combination with Conjunctive Groundwater Use. These changes are primarily attributable to the introduction of common bean and potato into the three-year rotation, both of which have lower yields than the crops they replace. Irrigation water-use efficiency remained unchanged. Consequently, these outcomes cannot be interpreted as either an improvement or deterioration relative to present-day conditions without considering their economic implications (see next section). Nevertheless, a slight increase in irrigated wheat was observes, reflecting improved soil nutrient conditions associated with the rotation system.

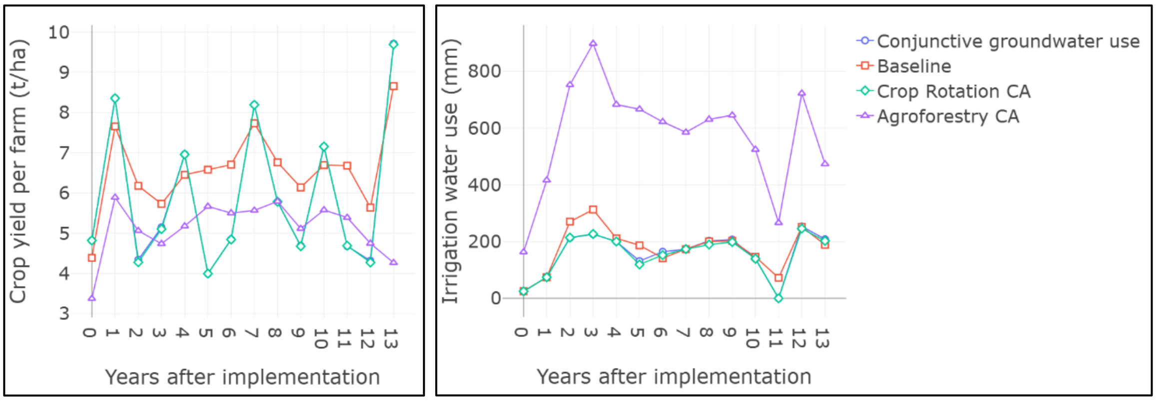



**Figure 19**– Annual crop yield (dry weight, left) and irrigation water use (right) since implementation (average across all crops) for all Best Management Practices in the eastern Koga command area (subbasin 14 – see Figure 13), compared with present-day (Baseline) conditions.

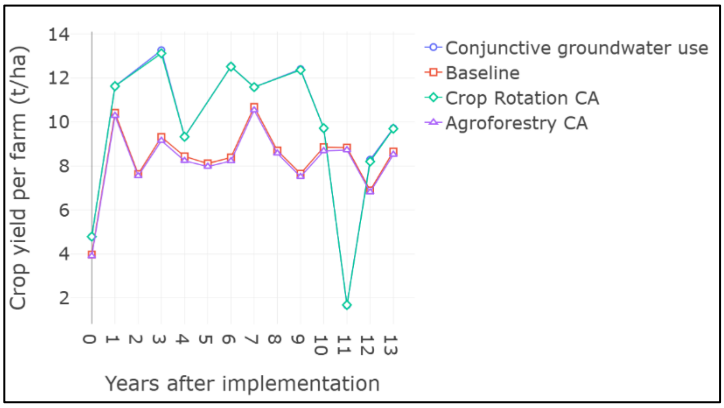



**Figure 20** – Annual crop yield (dry weight) for irrigated wheat since implementation, for all Best Management Practices in the eastern Koga command area (subbasin 14 – see Figure 13)

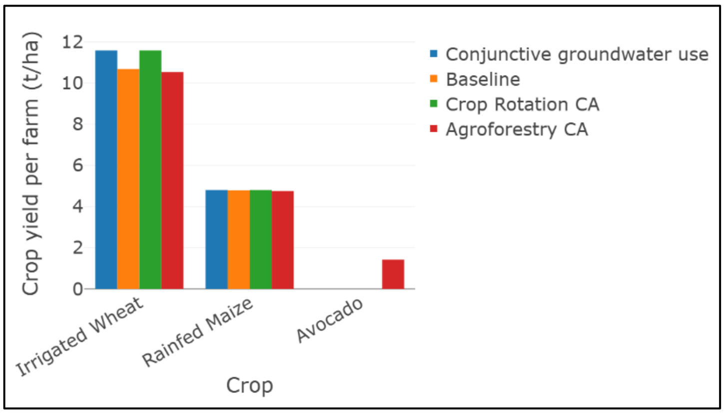



**Figure 21** – Annual crop yield per crop (dry weight) for the middle of the time series (irrigated wheat in the Crop Rotation BMP, right), for all Best Management Practices in the eastern Koga command area (subbasin 14 – see Figure 13), compared with present-day (Baseline) conditions.

In contrast, the Agroforestry BMP resulted in substantially lower yields and higher irrigation water use, leading to a decline in water-use efficiency. This outcome is mainly driven by the lower yields and higher water requirements of avocado trees compared with the crops they replace. Lower yields should not necessarily be viewed as a negative outcome, as they are an inherent consequence of changing crop types and may be offset by other benefits such as higher market prices, improved income diversification, or enhanced system resilience. However, the increased irrigation demand associated with avocado cultivation represents a clear trade-off that should be carefully considered.

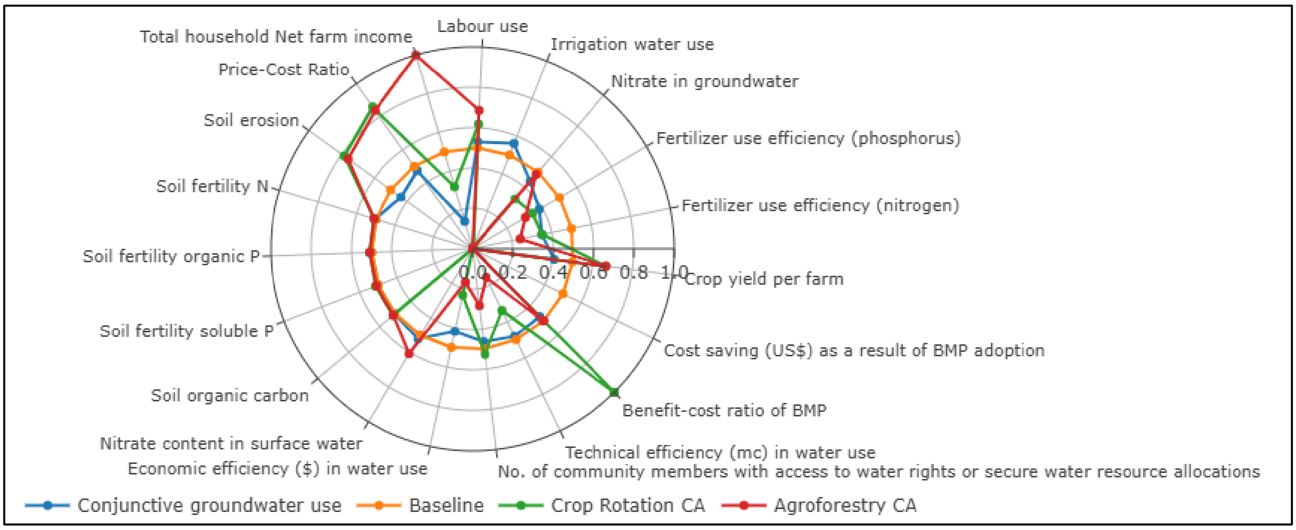



**Figure 22** – Scoring of Key Performance Indicators for the Koga Command Area, for the Baseline and all Best Management Practices; scores rank from 0 (worst) to 1 (best), with Baseline scoring 0.5.

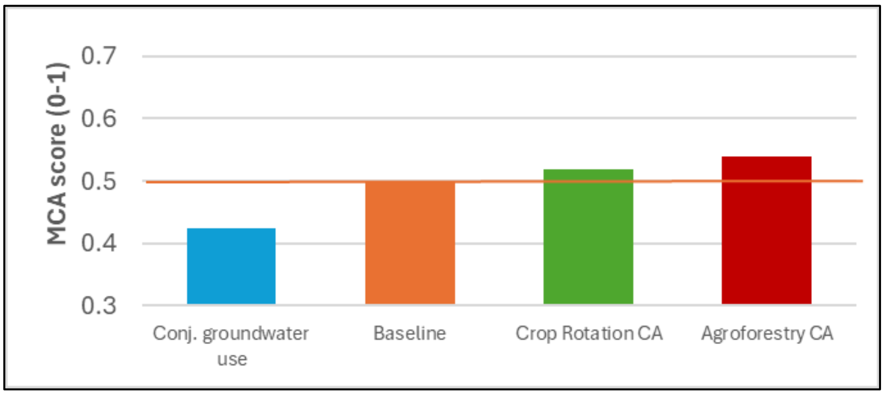



**Figure 23** – Multi-Criteria Analysis score for the Baseline and all Best Management Practices for the Koga Command Area, calculated from weighted Key Performance Indicators.

The scores for each KPI under the different BMPs implemented in the Command Area are shown in Figure 22, while the corresponding MCA results are shown in Figure 23. Overall, both the Agroforestry and Crop Rotation BMPs are expected to perform better than the baseline scenario conditions. Agroforestry improves the price-cost ratio, and consequently net farm income, primarily due to increased revenues despite higher production costs and limited cost savings. These economic benefits outweigh the negative impacts associated with substantially higher water use for a comparable level of production. As a result, Agroforest exhibits lower technical and economic water-use efficiency and lower fertilizer-use efficiency which may pose risks to long-term water availability.

The Crop Rotation BMP delivers more moderate improvements in the price-cost ratio, driven by a combination of increased yields and reduced production costs. Although some negative impacts on net farm income and fertilizer-use efficiency remain, these are less pronounced than in the Agroforestry scenario, resulting in a favourable benefit-cost ratio. The performance of both BMPs could potentially be improved through improved fertilization management practices.

In contrast, Conjunctive Groundwater Use, when combined with Crop Rotation, is expected to perform less favourably than current system. While it shares many of the advantages and disadvantages of Crop Rotation BMP, the conditional infrastructure and operational costs associated with groundwater use generate relatively limited additional benefits, thereby reducing the overall benefit–cost ratio compared with Crop Rotation alone. However, the MCA does not explicitly account for the increased resilience of water supplies provided by conjunctive water use. By supplementing reservoir water with groundwater resources during periods of high demand, this BMP may improve the reliability and security of irrigation water delivery within the Koga Command Area, an important benefit that is not fully captured by the selected KPIs.

**Koga Upstream Catchment**

The impacts of BMP implementation in the non-irrigated upstream catchment of the Koga are shown in Figure 24 for crop yield (left) and soil erosion rates (right). Both the Eucalyptus plantation and Forage Grass increase overall biomass production relative to the baseline scenario. However, these increases correspond to the production of wood and fodder, respectively, rather than food crops, implying a partial reduction in food production within the catchment. At the same time, both BMPs substantially reduce soil erosion with forage grass providing the greatest erosion-control benefits.

The Crop Rotation BMP results in more variable yields than the baseline. Peak yields occur every three years when maize is growing within the rotation cycle. Soil erosion rates also exhibit greater interannual variability than the baseline. In some years, erosion exceeds baseline levels when intense rainfall coincides with teff or maize cultivation (e.g., years 7 and 8). In contrast, erosion rates are lower when high rainfall occurs during years in which lupin is cultivated (e.g., year 12), reflecting the improved soil protection and conservation benefits associated with this leguminous crop.

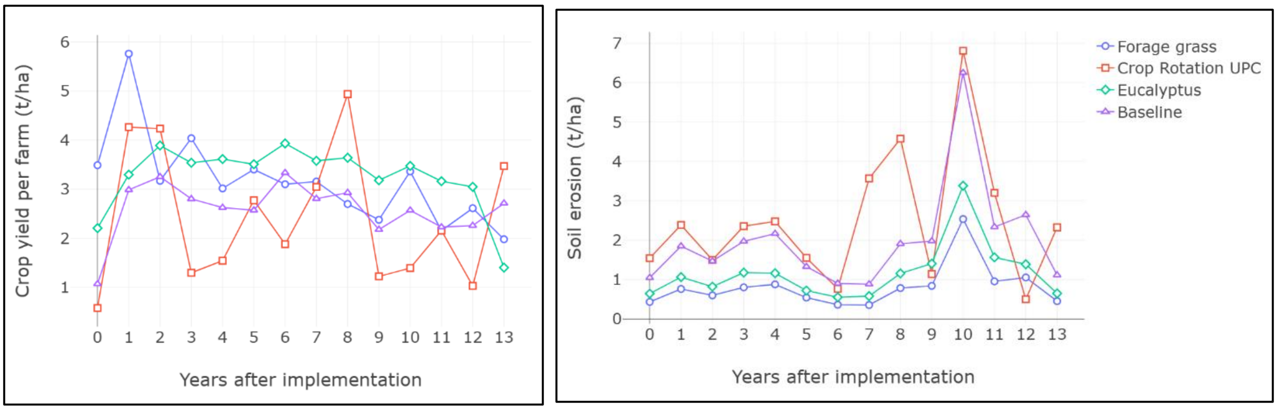



**Figure 24** – Annual crop yield (dry weight, left) and soil erosion (right) since implementation (average across all crops) for all Best Management Practices in the Koga upstream catchment area (subbasin 40 – see Figure 12), compared with present-day (Baseline) conditions.

The MCA required a revision of the KPI weights presented in Figure 1, as indicators related to irrigation water use are not applicable to the non-irrigated upstream catchment catchment. The revised weight scheme is shown in Figure 25, placing greater emphasis on crop production and soil-related indicators while reducing the importance of water-related indicators. Only KPIs associated with water quality impacts were retained.

The scores for each KPI under the different BMPs are shown in Figure 26, while the corresponding MCA results are shown in Figure 27. Overall, the Eucalyptus and Forage Grass BMPs show a similar improvement profile. Both measures provide substantially benefits for soil erosion control while also reducing labour requirement and production costs. These advantages contribute to higher net farmer income and improved fertilizer-use efficiency as an additional co-benefit. When comparing the two options, Eucalyptus plantation performs better in terms of price-cost ratio and generates greater cost savings, whereas Forage Grass achieves a less favourable economic performance.

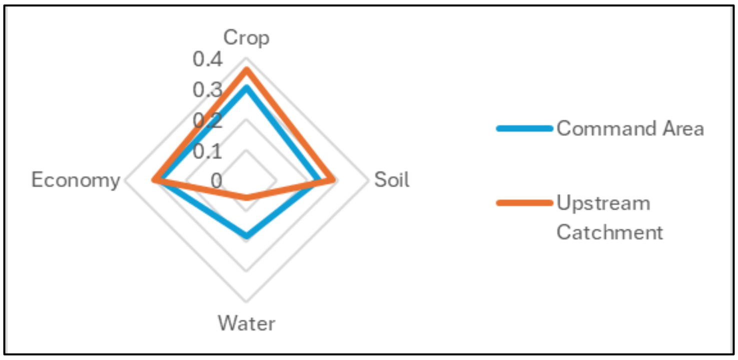



**Figure 25** – Weights assigned to each Key Performance Indicator group by Koga regional managers, for the Command Area (with irrigation) and the Upstream Catchment (without irrigation); in each area, the total sum of weights is 1.

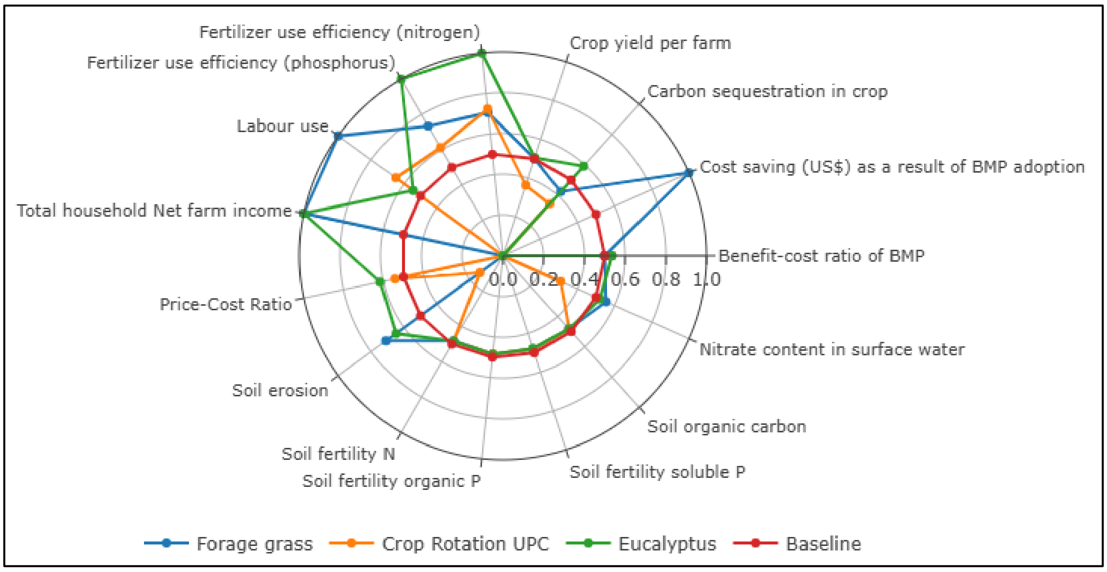



**Figure 26** – Scoring of Key Performance Indicators for the Koga Upstream Catchment for the Baseline and all Best Management Practices; scores rank from 0 (worst) to 1 (best), with Baseline scoring 0.5.

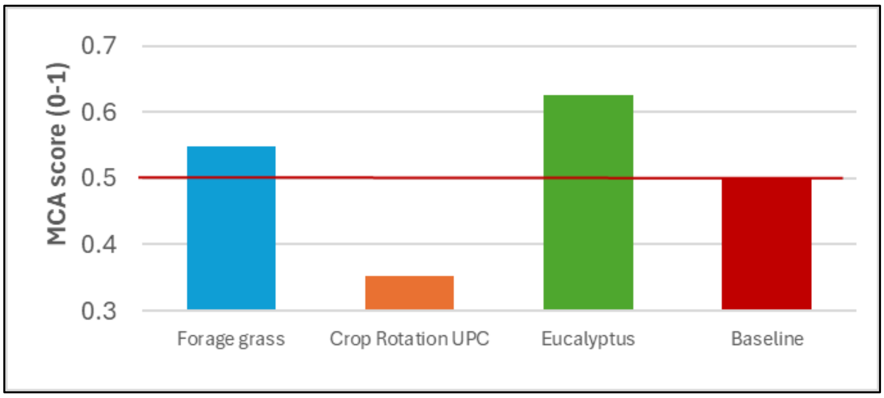



**Figure 27** – Multi-Criteria Analysis score for the Baseline and all Best Management Practices for the Koga Upstream Catchment, calculated from weighted Key Performance Indicators.

In contrast, the Crop Rotation BMP is assessed as performing less favourably than present-day practices. Although the measure reduces labour requirements and improves fertilizer-use efficiency, these benefits are offset by lower crop yields, resulting in reduced net farm income. In addition, the rotation system may lead to increased soil erosion in some years, depending on the timing of rainfall events and crop cover conditions. It should be noted, however, the MCA does not account for the contribution of the Crop Rotation to food security. Unlikely the Eucalyptus plantation and Forage Grass scenarios, which partially replace food production with wood or fodder production, the Crop Rotation BMP maintains agricultural food production within the catchment. This potential benefit is not reflected in the KPI framework and may therefore lead to an underestimation of the overall value of the measure.

# 5. Detailed assessment for the Hola and Bura command areas, Kenya

## 5.1. Model application

The model was applied to the entire Tana River Basin, including agricultural fields, rangelands, groundwater resources, and the stream network. However, it was only detailed for the irrigated fields within the Hola and Bura command areas, which cover approximately 9.1 and 48.5 $Km^2$, respectively (Figure 28). Only results from these two command areas were included in the Toolbox. The irrigation canal connecting the Tana River to the irrigation schemes was simulated in an abstract manner.

Present-day conditions were simulated using a 31-year model run. Current cropping system include rice, cotton, and limited fruit tree cultivation, predominantly mango (Figure 29). Irrigation is currently based on flood irrigation using furrows. However, farmers frequently express concerns about the limited and irregular water supply delivered through the canal network.

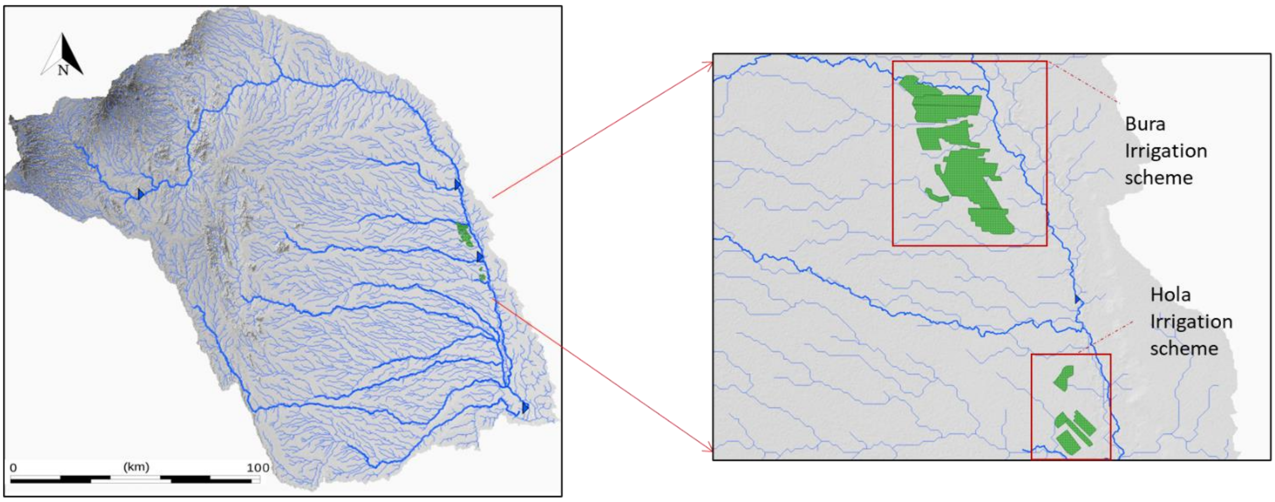



**Figure 28 –** Map of the Tana watershed (left), and location of the Hola and Bura irrigation schemes (right).

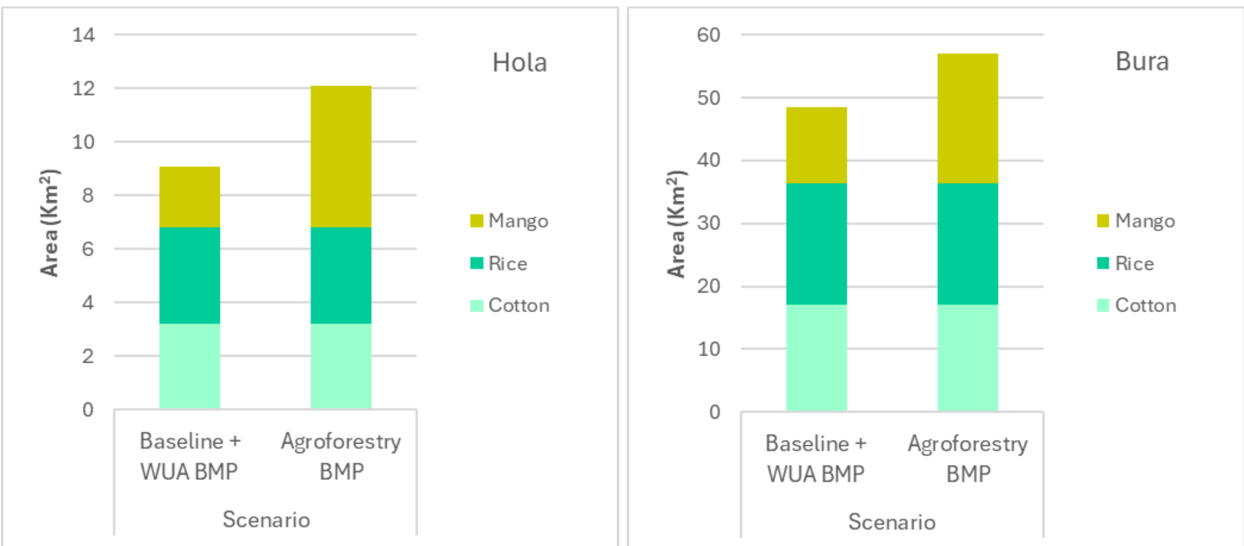



**Figure 29 –** Crops considered in the model for the Hola (left) and Bura (right) irrigation schemes, and respective areas.

## 5.2. BMP scenarios

The BMPs were implemented only in the Hola and Bura command areas. The following BMPs were selected for implementation:

- Agroforestry: Conversion of additional blocks to mango trees to increase farm income, combined with the establishment of vegetated strips as hedges around the remaining fields for nature conservation.
- Water Users' Association: aiming at increasing water availability for farmers, including increased water canal flow, enhanced storage capacity within the canal network, and improved irrigation efficiency.
- Agroforestry plus WUA: a combination of both measures.

### Agroforestry

Building on existing permanent crop cultivations, local stakeholders proposed a more structured permanent cropping system that integrates fruit trees for income generation with indigenous and forage tree species for ecological and social benefits.

The regional stakeholders defined which irrigation blocks would receive the tree crops. They also identified three main objectives for this intervention:

- Enhancing farm income through the cultivation of high-value fruit trees such as mango, citrus, pawpaw, and coconut, since these species are well adapted to the local climate and have established market demand both locally and regionally;
- Promoting environmental protection through the planting of indigenous trees along feeder canals and exposed areas to stabilize canal banks, prevent erosion, and improve microclimatic conditions;
- Reducing land-use conflicts between pastoralists and farmers by introducing forage trees along field boundaries, creating designated buffer zones that provide livestock feed and protecting crops from damage.

The resulting agroforestry configuration therefore combines fruit tree cultivation within selected irrigation blocks with the establishment of vegetated hedgerows composed of indigenous and forage trees around cultivated fields and along feeder canals. In addition to their productive and protective functions, these hedgerows also act as windbreaks and ecological corridors, contributing to landscape connectivity, biodiversity conservation and ecosystem resilience.


**Figure 30** – Identified zones for agroforestry implementation in the Bura (left) and Hola (right) schemes.

In operational terms, mango trees were selected as the principal fruit crop, reflecting both farmer preferences and their suitability to the climatic condition of the Tana River Basin. Furrow irrigation, which remains the dominant method in the command areas, was retained in the BMP design to ensure compatibility with existing infrastructure and current farmer practices. A standard mineral fertilization scheme was assumed, following local crop management norms, with nutrient adjustments made for tree crops.

Stakeholders identified specific irrigation areas within both the Hola and Bura schemes for agroforestry implementation (Figure 30). In Bura, four areas were designated covering a total of 837 ha; while in Hola, two areas were selected, covering a total of 304 ha. Together, these areas represent an expansion of approximately 1,141 ha of new agroforestry plots. When combined with the existing 1,440 ha already under tree crops, the total area under agroforestry increases to roughly 2,580 ha.

Across these sites, the remaining cultivated fields were bordered by vegetated hedgerows established as 2m-wide buffer strips. These hedgerows serve as windbreaks, ecological corridors, and protective boundaries around irrigated plots, although these ecosystem services could not be explicitly simulated by the model.

Through this integrated approach, the agroforestry BMP is expected to diversify farm income sources, improve soil and water conservation, and strengthen ecological resilience of the Hola and Bura irrigation systems.

**Water Users' Association**

In Kenya, the establishment of Water Users' Associations (WUAs) has been promoted as a means to enhance equity in water distribution, improve coordination among farmers, and organize the maintenance of irrigation infrastructure. Many farmers view WUAs as a practical solution to recurrent conflicts over water access and to inefficiencies in the management of canals and maintenance schedules. However, experiences from other irrigation schemes across the country reveal that the implementation of WUAs can also become a source of contention, particularly where issues of leadership, accountability, or unequal representation arise.

In this project, the simulation of the WUA's role was represented through the set of possible actions and water management improvements that could result from its effective implementation. The proposed actions include:

- enhancing pumping capacity to increase the water availability within the canal network;
- reducing conveyance losses and improving canal flow through regular desilting and maintenance;
- securing water availability during critical irrigation periods by introducing local storage options; and
- minimizing field-level runoff losses through better land levelling.

Collectively, these measures aim to strengthen irrigation reliability, improve water-use efficiency, and reinforce the organizational capacity of WUAs as central actors in coordinated water management.

Within the modelling framework, the WUA was operationalised through a series of parameter adjustments designed to emulate both the physical and organisational improvements anticipated from its implementation. Specifically, canal water availability was increased by 30%, representing the synergistic effects of enhanced pumping capacity and the introduction of localized water storage systems. Conveyance efficiency was raised from 60% to 75%, capturing the expected reduction in transmission losses resulting from regular desilting, canal lining, and improved maintenance coordination under a functioning WUA structure.

At the field scale, irrigation-induced surface runoff was reduced from 50% to 35%, reflecting the expected benefits of improved land levelling and more uniform water distribution across agricultural plots. These parameter changes were initially simulated independently to assess the contribution of each management action and subsequently combined into an integrated scenario.

The resulting WUA scenario represents an irrigation system characterised by more reliable water delivery, improved conveyance efficiency, and improved on-farm water management, consistent with the outcomes anticipated from an effectively functioning WUA.

**Agroforestry plus WUA**

Regional managers proposed an integrated BMP scenario that combines the Agroforestry and Water Users' Association measures described above. This combined approach reflects both the technical priorities identified during the stakeholder consultations and the practical feasibility identified by local actors.

## 5.3. BMP assessment

Figure 31 shows the impact of BMP implementation on crop yield and irrigation water use in the Bura irrigation scheme; results for the Hola scheme were similar.

Overall, both WUA and Agroforestry BMP led to small increases in crop yield and irrigation water use. As irrigation water use increased proportionally more than crop production, both measures resulted in a slight decline in water-use efficiency. When the two BMPs were combined, the increase in yield and irrigation water use became pronounced, but water-use efficiency declined further, particularly during years with high rainfall.

One notable benefit of the combined agroforest plus WUA is its ability to reduce yield losses during dry years characterised by high irrigation demand. By improving water availability and delivery, the WUA component enables higher irrigation rates during critical periods, thereby helping to stabilize crop production under less favourable climatic conditions.

The scores for the different KPIs are shown in Figure 32, with the MCA scores in Figure 33. The Water Users' Association BMP shows a good benefit-cost ratio despite increasing implementation and operational costs, while having limited effects on most of the other KPIs.

In contrast, the Agroforestry BMP shows only small improvements in soil erosion control, and required implementation costs, resulting in a comparatively weaker overall performance.

The combined agroforestry plus WUA scenario was assessed as performing less favourable than the present-day conditions. Although the scenario achieved a positive benefit-cost ratio and produced some improvements in erosion control and nitrogen-use efficiency, these benefits were outweighed by a lower price-cost ratio, which reduced net farm income. In addition, technical and economic water-use efficiency declined because of increased irrigation requirements.

It is important to note, however, that the MCA did not capture several important co-benefits associated with these BMPs. For example, WUA scenario may facilitate future expansion of irrigation areas through improved water management and infrastructure performance. Similarly, Agroforestry scenario can contribute to crop diversification, increased livelihood resilience, enhanced ecosystem services, and reduced conflicts between farmers and pastoralists. These benefits are not reflected in the selected KPI framework and may therefore lead to an underestimation of the overall value of the proposed interventions.

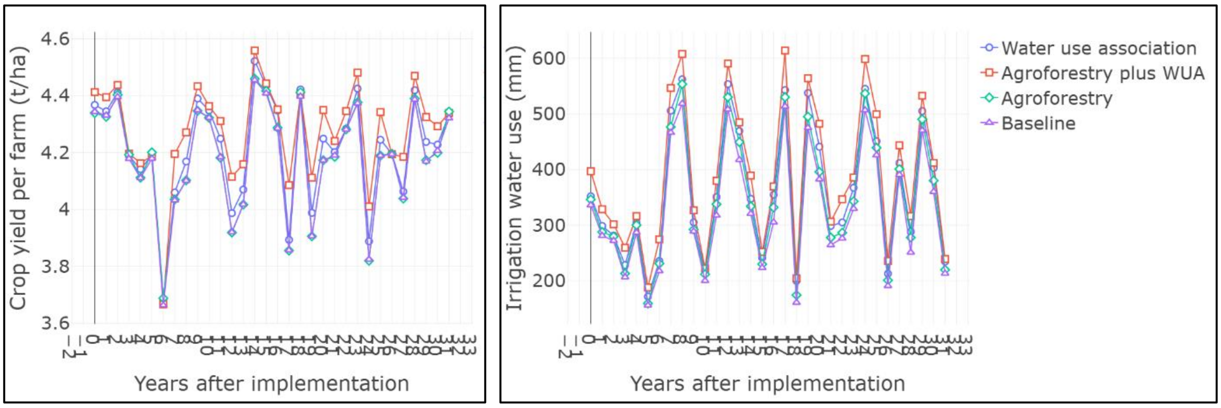



**Figure 31** – Annual crop yield (dry weight, left) and irrigation water use (right) since implementation (average across all crops) for all Best Management Practices in the Bura command area (see Figure 28), compared with present-day (Baseline) conditions.

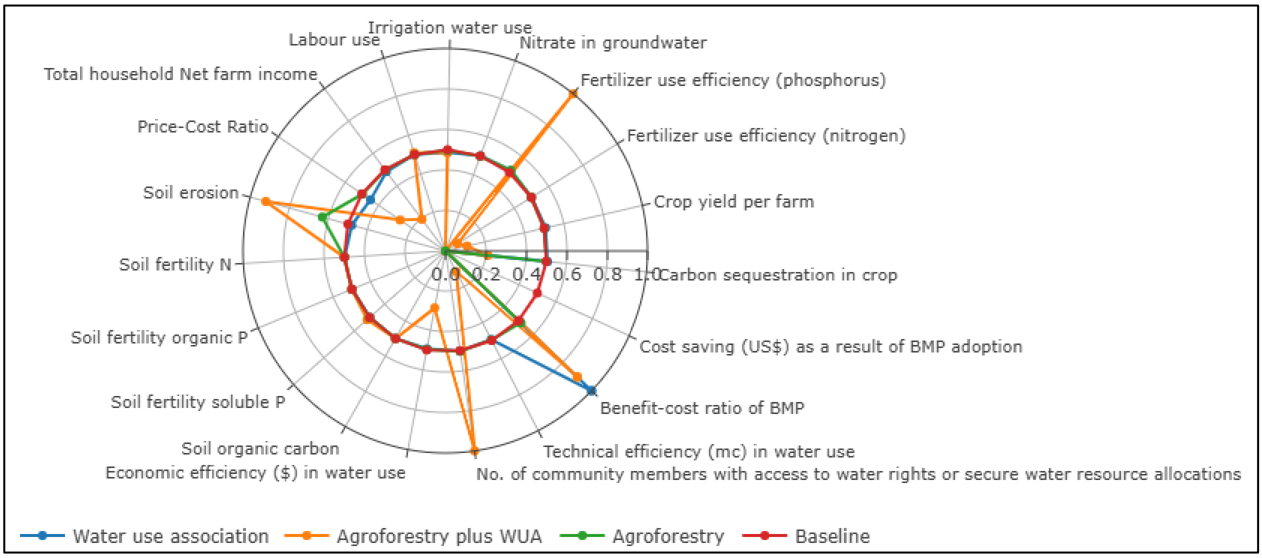



**Figure 32** – Scoring of Key Performance Indicators for the Hola and Bura command areas, for the Baseline and all Best Management Practices; scores rank from 0 (worst) to 1 (best), with Baseline scoring 0.5.

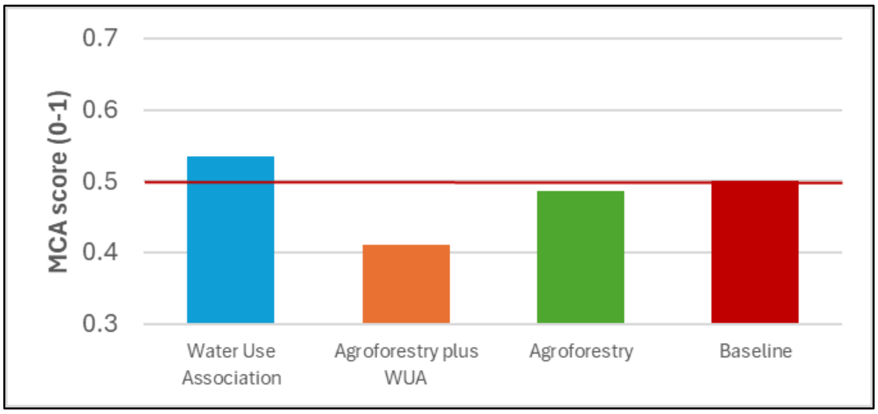



**Figure 33** – Multi-Criteria Analysis score for the Baseline and all Best Management Practices for the Hola and Bura command areas, calculated from weighted Key Performance Indicators.

# 6. Detailed assessment for the Gezira irrigation scheme, Sudan

## 6.1. Model application

The model was applied to the entire Gezira Irrigation Scheme, covering the full command area of approximately 6030 km$^2$ (Figure 34). The modelling framework focuses primarily on farm-level processes; while the irrigation canal network is represented in an abstract manner to account for water distribution and conveyance losses along the network. Each sub-basin in Figure 34 represents irrigation blocks supplied by a specific section of the main irrigation canal. The simulation captures the main cropping seasons, fertilizer applications and irrigation cycles implemented within the scheme, thereby representing the interaction between water delivery and crop growth over time. The model includes the main cultivated crops: Cotton, Sorghum, Wheat, and Peanut (Figure 35). Present-day conditions were simulated using a 32-year model run.

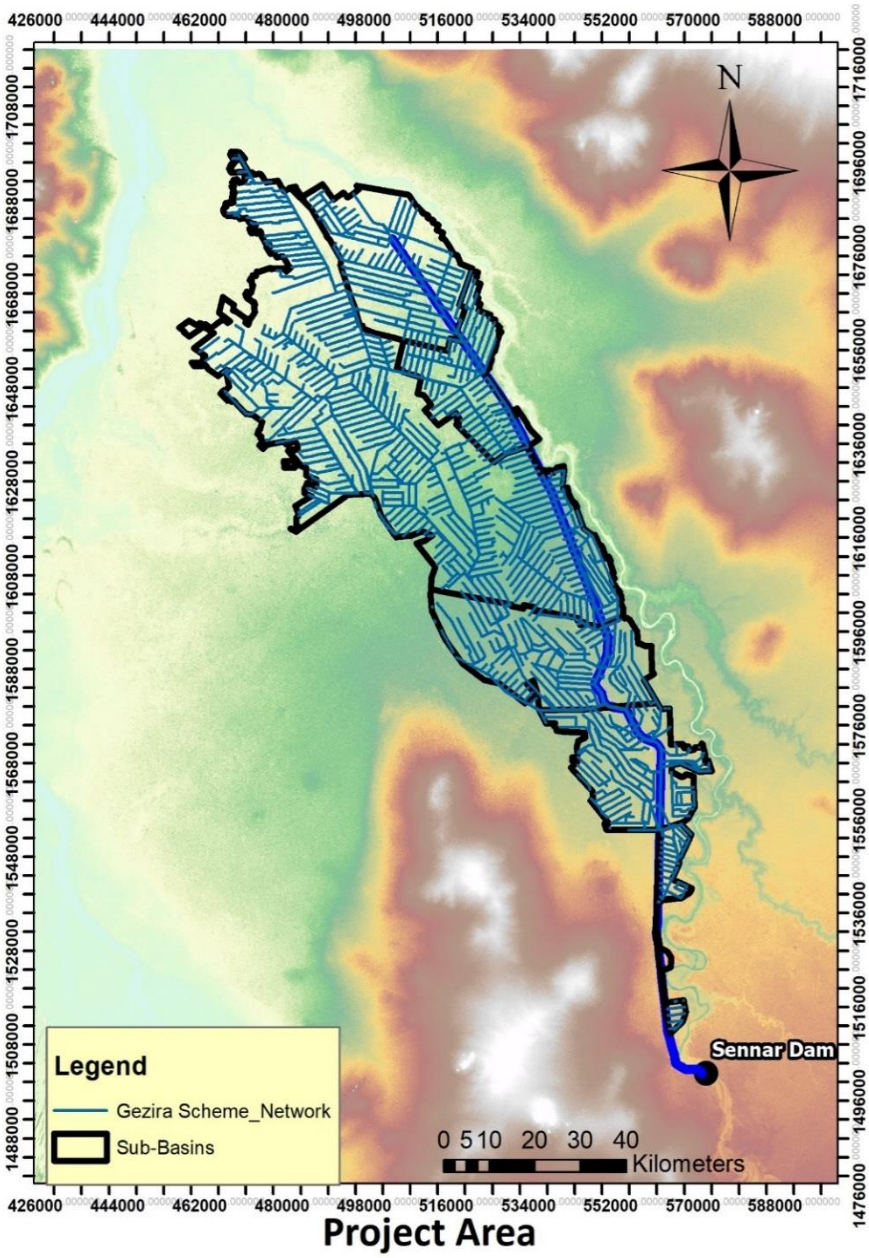



**Figure 34** – Map of the Gezira study area, including the simulated sub-basins (in this case, irrigation blocks) and irrigation canals; while the map shows detailed canal branches, these were not included in the model.

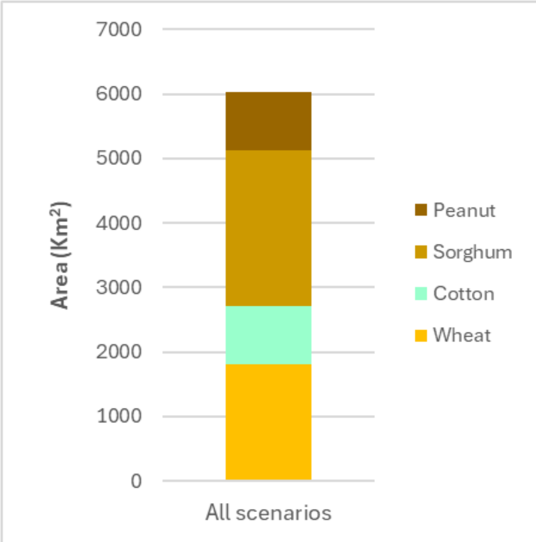



**Figure 35** – Crops considered in the Gezira model and respective areas

Flood irrigation using furrows is supplied by water from the Sennar Dam and distributed through the irrigation canal network, with variations in timing and quantity reflecting existing operational constraints in the scheme (Elshaik et al, 2018). Stakeholder consultations highlighted several key challenges in the Gezira Scheme related to water distribution and allocation. These challenges are primarily associated with inadequate maintenance of canals and hydraulic structures, as well as broader operational inefficiencies in the management of both irrigation scheme and the Sennar Dam.

Poorly maintained canals have a reduced conveyance capacity and contribute to significant water losses during transport. In addition, system operation is not always well coordinated, resulting in irregular water delivery. Consequently, farmers located closer to the water source may receive more water than required, while those at the tail-end of canals frequently experience water shortages or, in some cases, abrupt excess flows. A further consequence of these operational inefficiencies is delayed water delivery to farmers during the growing season. As a result, planting is often postponed beyond the optimal sowing window. These delays can negatively affect crop yields, as crops may be exposed to higher temperatures or water stress during critical growth stages.

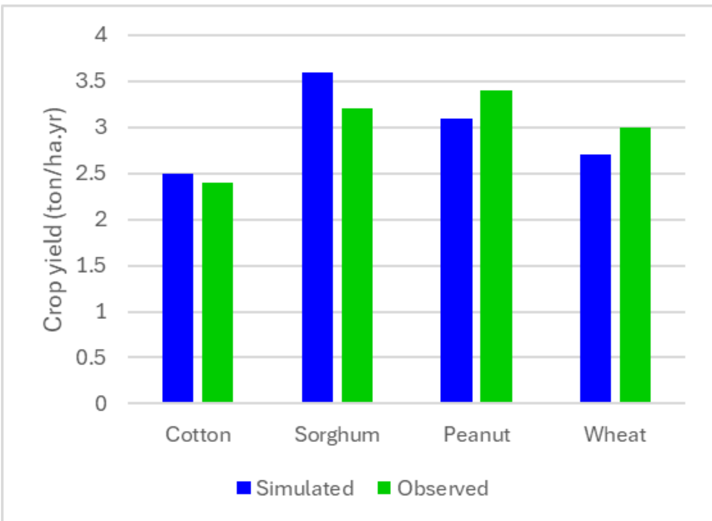



**Figure 36** – Model performance for crop yield in Gezira.

Model calibration was conducted using crop yield data for the baseline scenario. Simulated yields were compared with values reported in the literature, as well as with information provided by farmers and local stakeholders. The results showed generally good agreement (Figure 36), with an average error of -0.5%.

## 6.2. BMP scenarios

The following BMPs were selected for implementation in the Gezira irrigation scheme:

- Water Users' Association A: Advance the start of the growing season by ensuring that irrigation water is made available earlier in the year, thereby enabling earlier planting.
- Water Users' Association B: Building on WUA A, improve water distribution among farmers by increasing conveyance efficiency and implementing stricter irrigation scheduling to enhance the coordination and timing of water deliveries.

**Figure 37** – Meeting with stakeholders in Gezira.

**Water Users' Association A – early planting through improved canal maintenance**

The early planting BMP focuses on adjusting planting dates so that crops grow under more favourable climatic and hydrological conditions. In this study, early planting is implemented by shifting the cropping calendar forward in accordance with recommendations from the Agriculture Research Center. This adjustment enables crops to make better use of available water resources and to avoid water stress during later stages of the growing season.

The BMP is applied to the main crops grown within the scheme. Stakeholders indicated that earlier planting is feasible if irrigation scheduling is improved and water delivery becomes more reliable. This, in turn, depends on some repairs of key infrastructures within the Gezira scheme, including annual maintenance such as canal repairs and desilting, as well as broader improvements in water management. The detailed operational management schedule is presented in Table 5.

**Table 5** – Comparison of irrigation operations between the baseline and the WUA A BMPs.

| | Irrigation start date | | Irrigation amount (mm/yr) | |
|---|---|---|---|---|
| **Crop** | **Baseline** | **WUA A and B** | **Baseline and WUA A** | **WUA B** |
| Cotton | 1-Jul | 1-Jun | 1000 | 1200 |
| Sorghum | 10-Jul | 10-Jun | 700 | 900 |
| Peanut | 5-Jul | 5-Jun | 600 | 1100 |
| Wheat | 1-Dec | 1-Nov | 600 | 800 |

**Water Users' Association B – increase in water distribution through canal renovation**

This BMP represents a broader rehabilitation of the Gezira scheme, combining the water management and canal maintenance measures of WUA A with substantial investments in the desilting of canals and the renovation of gates and other water control infrastructure. In the model, this was simulated by increasing conveyance efficiency from 50% to 70%, and by allowing higher water availability during irrigation applications, as shown in Table 5. The BMP also incorporates early planting measures defined under WUA A, as improved system maintenance is assumed to enable more reliable and earlier access to irrigation water, thereby meeting farmers' demands for an earlier start to the growing season.

## 6.3. BMP assessment

The impacts of the BMPs on crop yields are shown in Figure 38. Spatial variability is not presented, as differences are primarily driven by crop types rather than spatial heterogeneity, and irrigation water applications remain unchanged outlined in Table 5. The results indicate that early planting under both the WUA A and WUA B leads to an increase in crop yields across all crops. This improvement is mainly due to better alignment of crop growth stages with seasonal climatic conditions, thereby reducing stress during critical growth periods. Under WUA B, yields increase further, as a result of higher irrigation availability, which address insufficient irrigation reported by local farmers. In both WUA scenarios, water-use efficiency also increases; in WUA B, this occurs despite the increase in total irrigation water use.

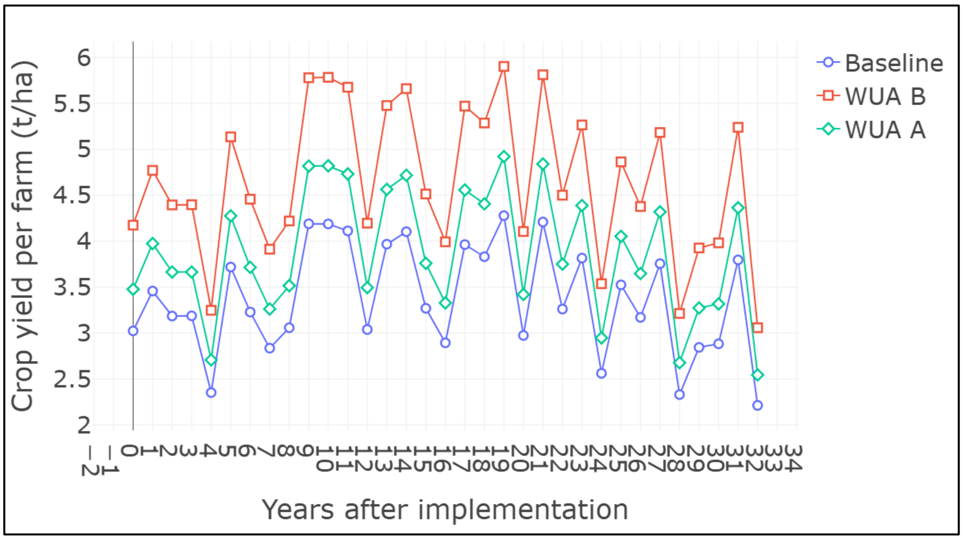



**Figure 38** – Annual crop yield (dry weight) since implementation (average across all crops) for all Best Management Practices in the middle of the Gezira scheme (see Figure 34), compared with present-day (Baseline) conditions.

The performance of each BMP across the selected KPIs is shown in Figure 39, while Figure 40 shows the corresponding MCA scores. Overall, both BMPs exhibit similar effects on the same set of KPIs, although the magnitude of the impacts is considerably greater for WUA B. Both BMPs lead to increases in crop yield with relatively minor changes in input use, resulting in higher water- and fertilizer-use efficiency. Consequently, both measures achieve a good benefit-cost ratio, despite the associated implementation costs. The WUA B BMP also results in higher net farmer income and, interestingly, a reduction in water contamination, as crops make more efficient use of the applied fertilizers. Feedback from stakeholders during project workshops confirmed that these results are consistent with field experience. However, the stakeholders also emphasised that improvements in water management depend strongly on coordination between farmers and irrigation authorities, which remains the principal challenge for the effective implementation of both WUA BMPs.

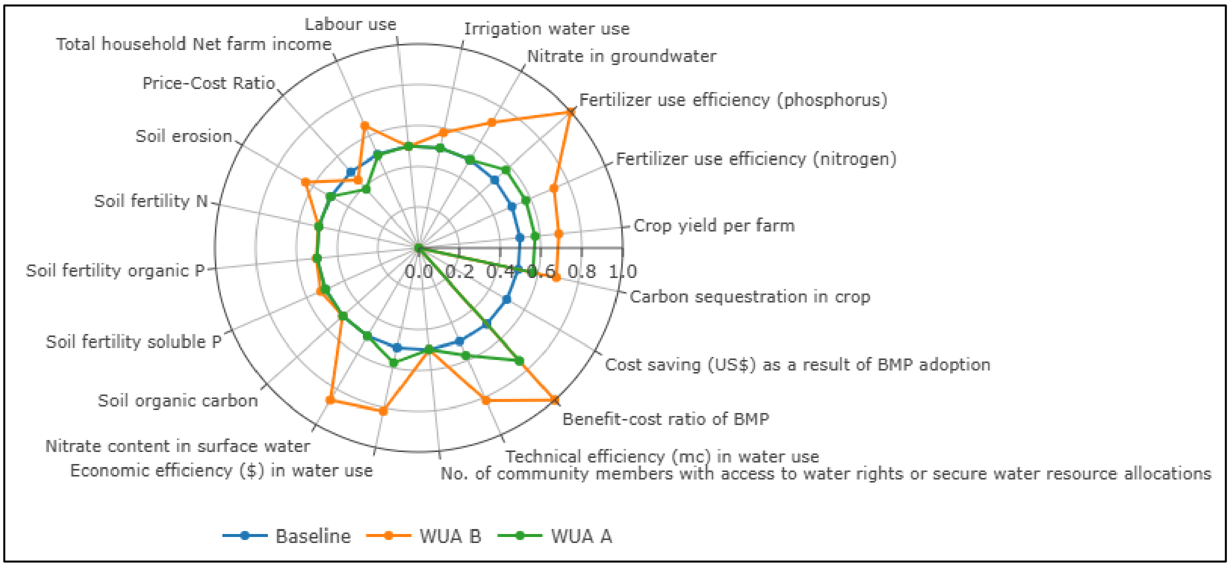



**Figure 39** – Scoring of Key Performance Indicators for the Gezira irrigation scheme, for the Baseline and all Best Management Practices; scores rank from 0 (worst) to 1 (best), with Baseline scoring 0.5.

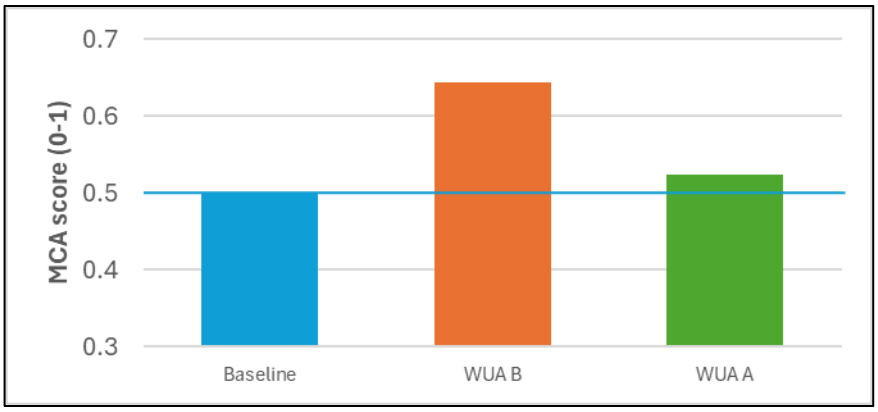



**Figure 40** – Multi-Criteria Analysis score for the Baseline and all Best Management Practices for the Gezira irrigation scheme, calculated from weighted Key Performance Indicators.

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