CGIAR
SCIENCE FOR A FOOD-SECURE FUTURE

Technical Report

# Guideline on Conjunctive Use of Surface Water and Groundwater for Irrigation

## Demonstration on the Meki Catchment, Central Rift Valley, Ethiopia

Meron Teferi Taye, Girma Yimer Ebrahim, Kirubel Mekonnen, Mulugeta Tadesse, Mohammed Abdella, and Abdulkarim H. Seid

November 2026



## Authors

**Meron Teferi Taye**, Researcher - Water and Climate Systems, International Water Management Institute (IWMI), Addis Ababa, Ethiopia (meron.taye@cgiar.org)
**Girma Yimer Ebrahim**, Researcher - Hydrogeology and Water Resources, IWMI, Addis Ababa, Ethiopia (g.ebrahim@cgiar.org)
**Kirubel Mekonnen,** Regional Researcher - Water Systems Modelling, IWMI, Addis Ababa, Ethiopia (k.gebreyesus@cgiar.org)
**Mulugeta Tadesse,** Spatial Data Scientist, IWMI, Addis Ababa, Ethiopia (mulugeta.tadesse@cgiar.org)
**Mohammed Abdella**, Research Officer I - Water Data Science, IWMI, Addis Ababa, Ethiopia (m.abdella@cgiar.org)
**Abdulkarim H. Seid**, Representative for Ethiopia and East Africa, IWMI, Addis Ababa, Ethiopia (a.seid@cgiar.org)

## Author contributions

Conceptualization: Meron Teferi Taye, Girma Yimer Ebrahim, Kirubel Mekonnen, Mulugeta Tadesse, Mohammed Abdella, Abdulkarim H. Seid; Methodology: Meron Teferi Taye, Girma Yimer Ebrahim, Kirubel Mekonnen, Mulugeta Tadesse, Mohammed Abdella, Abdulkarim H. Seid; Formal analysis: Meron Teferi Taye, Girma Yimer Ebrahim, Kirubel Mekonnen, Mulugeta Tadesse, Mohammed Abdella, Abdulkarim H. Seid; Writing – original draft: Meron Teferi Taye; Writing – review & editing: Meron Teferi Taye, Girma Yimer Ebrahim, Kirubel Mekonnen, Mulugeta Tadesse, Mohammed Abdella, Abdulkarim H. Seid; Visualization: Mulugeta Tadesse, Girma Yimer Ebraim, Kirubel Mekonnen, Meron Teferi Taye; Supervision: Abdulkarim H. Seid.

## Acknowledgments

This work was carried out under the CGIAR Policy Innovations Program. We would like to thank all funders who supported this research through their contributions to the CGIAR Trust Fund (www.cgiar.org/funders).

## Suggested citation

Taye, Meron Teferi, Girma Yimer Ebrahim, Kirubel Mekonnen, Mulugeta Tadesse, Mohammed Abdella, and Abdulkarim H. Seid. 2026. *Guideline on Conjunctive Use of Surface Water and Groundwater for Irrigation: Demonstration on the Meki Catchment, Central Rift Valley, Ethiopia.* International Water Management Institute (IWMI).

© 2026 International Water Management Institute. Some rights reserved. This work is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0).

**Front cover photo:** Water pond for irrigation after pumping from groundwater well in Misrak Meskan woreda (*photo*: Meron Teferi Taye)
**Back cover photo:** Spring water used for irrigation in Silte woreda (*photo*: Meron Teferi Taye)

## Disclaimer

This publication has been prepared as an output of the CGIAR Policy Innovations Program and has not been independently peer-reviewed. Responsibility for editing, proofreading, layout, opinions expressed and any possible errors lies with the authors and not the institutions involved. Boundaries used in the maps do not imply the expression of any opinion whatsoever on the part of CGIAR concerning the legal status of any country, territory, city, or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Borders are approximate and cover some areas for which there may not yet be full agreement.

# Contents

List of Figures ..... 3
Acronyms and abbreviations ..... 4
Summary ..... 6
1. Introduction: Why conjunctive use matters ..... 7
About this guideline 8
2. Framework for conjunctive water use assessment ..... 9
Step 1: Irrigated area estimation 10
Step 2: Irrigated water demand estimation 12
Step 3: Water resources estimation 13
Assessing hydro-meteorological data 13
Surface water estimation 14
Groundwater estimation 15
Step 4: Conjunctive water use assessment 16
Step 5: Sustainability limit for water abstraction 18
3. Demonstrating methodological framework: Meki catchment example ..... 18
Meki catchment and irrigation development 19
Step 1: Irrigation area mapping 20
Step 2: Irrigation water demand estimation 23
Step 3: Water availability estimation 26
Surface water availability estimation 26
Groundwater availability estimation 32
Step 4: Conjunctive use modeling 37
Step 5: Sustainability limits for water abstraction 41
Limitation of conjunctive water use modeling 42
Stakeholder consultations 43
4. Recommendations ..... 43
Technical considerations 43
Policy and implementation recommendations 43
5. References ..... 45
Annex ..... 48

# List of Figures

Figure 1: Proposed methodological framework to guide assessment of conjunctive use of water for irrigation .....10
Figure 2: Location of the Meki catchment in Ethiopia and the Rift Valley Lakes Basin. ARCPro GIS software is used to generate this map. .....20
Figure 3: Methodological workflow for mapping irrigated areas in the Meki catchment using Earth observation data, LSTM-based classification, and field validation .....21
Figure 4: Irrigated area per sub-catchment by source of irrigation water (surface water, groundwater, mixed surface water–groundwater) and for all water sources combined; dry season 2024/25. Sub-catchments in white indicate absence of irrigation.....22
Figure 5: Irrigated areas in the Meki catchment by source of irrigation water: surface water, groundwater, and mixed surface water and groundwater. Sub-catchments in white indicate absence of irrigated area. .....23
Figure 6: Seasonal gross irrigation water demand per sub-catchment by source of irrigation water, Meki catchment, December 2024 – March 2025. .....25
Figure 7: Dry-season gross irrigation demand (December 2024 - March 2025) by potential water source of the irrigated area: groundwater, surface water or mixed sources. Sources are inferred from irrigated farms' location, not from measured water abstractions .....26
Figure 8: Observed and SWAT-simulated monthly streamflow at the Meki gauging station, with catchment rainfall (inverted axis), 1984–2025 .....27
Figure 9: Long-term average annual water balance of the Meki catchment simulated with SWAT from 1984 to 2025 (depths in mm over the catchment). .....28
Figure 10: Long-term average monthly pattern of streamflow and baseflow for the Meki catchment.....28
Figure 11: Long-term average spatial distribution of dry-season (December–March) precipitation, actual evapotranspiration, water yield (WYLD) and total runoff (surface runoff (SURQ + lateral flow (LAT_Q) per sub-catchment simulated with SWAT (mm) .....29
Figure 12: Unmet irrigation demand (thousand $m^3$) under surface-water-priority allocation, during the 2024-2025 dry season (December 2024 – March 2025): (a) in surface-water-only irrigated areas; (b) in mixed surface water–groundwater irrigated areas. Note: SW – surface water; GW - groundwater .....30
Figure 13: Outcome of allocating surface water to meet the irrigation demand per sub-catchment within the Meki catchment, December 2024 – March 2025. .....31
Figure 14: Hydrogeological zones of the Meki catchment. ARCPro GIS software is used to generate this map.....34
Figure 15: Observed versus simulated groundwater levels for the steady-state MODFLOW model calibration. .....36
Figure 16: Comparison of monthly baseflow simulated by SWAT and by the MODFLOW SFR package at the Meki catchment outlet .....37
Figure 17: Long-term simulated spatial distribution of monthly irrigation water demand, surface water supply, surface water deficit, and groundwater supply across the Meki catchment during the irrigation season (December-March). .....39
Figure 18: The 81 sub-catchments as delineated by SWAT and selected two sub-catchments for conjunctive use demonstration .....40
Figure 19: Simulated monthly irrigation water supply in sub-catchment 24 during the growing season, showing surface water supply and the deficit met by groundwater. .....40
Figure 20: Simulated monthly irrigation water supply in sub-catchment 61 during the growing season, showing surface water supply and the deficit met by groundwater. .....41

## Acronyms and abbreviations

| | |
|---|---|
| AfSIS | Africa Soil Information Service |
| AG | Agricultural Water Use |
| CHIPRS | Climate Hazards Group InfraRed Precipitation with Station data |
| CWR | Crop Water Requirement |
| DEM | Digital Elevation Model |
| EMI | Ethiopian Meteorological Institute |
| EO | Earth Observation |
| EROS | Earth Resources Observation and Science |
| ESPA | EROS Science Processing Architecture |
| ET | Evapotranspiration |
| ETa | Actual Evapotranspiration |
| ETc | Crop Evapotranspiration |
| ETo | Reference Crop Evapotranspiration |
| EVI | Enhanced Vegetation Index |
| FAO | Food and Agriculture Organization |
| GHB | General Head Boundary |
| GIR | Gross Irrigation Requirement |
| GIS | Geographic Information Systems |
| GPS | Global Positioning System |
| GWET | Groundwater Evapotranspiration |
| HRU | Hydrologic Response Unit |
| Kc | Crop Coefficient |
| LSTM | Long Short-Term Memory |
| LULC | Land Use Land Cover |
| MAE | Mean Absolute Error |
| MODFLOW | Modular Hydrologic Model |
| NDVI | Normalized Difference Vegetation Index |
| NIR | Net Irrigation Requirements |
| NRMSE | Normalized Root Mean Square Error |
| NWT | Newton-Raphson formulation |
| Pe | Effective Rainfall |
| PEST | Parameter ESTimation |
| RMSE | Root Mean Square Error |

| | |
|---|---|
| SAR | Synthetic Aperture Radar |
| SFR | Streamflow-Routing |
| SRTM | Shuttle Radar Topography Mission |
| SSA | Sub-Saharan Africa |
| SSEBop | Operational Simplified Surface Energy Balance |
| SWAT | Soil and Water Assessment Tool |
| USDA | United States Department of Agriculture |
| USGS | United States Geological Survey |

## Summary

Irrigated agriculture is considered by both farmers and policy makers to be one of the key pathways to food security and adapting to less reliable rainfall, frequent droughts and floods, and increasing climate variability. As irrigated agriculture expands across catchments, relying on a single water source will increasingly become unsustainable and the use of both surface and groundwater sources in a coordinated way will become a necessity where both resources are available. However, there is a limited guidance on how to use these resources for African catchments such as in Ethiopia that are mostly dominated by smallholder farmers.

This guideline is a response to fill this information gap and sets out a practical approach to conjunctive use, defined as the coordinated management of surface water and groundwater for irrigation. This guideline covers why conjunctive use matters, how to assess it, and how it works in practice within the realities of farmers in Ethiopia with fragmented land and dynamic food production practices.

The guideline presents a methodological framework that consists of estimating available water resources in a specific basin, mapping actual irrigated area, quantifying irrigation water demand, and estimating water deficits and assessing sustainability. This information is drawn from hydrological modelling, remote sensing, and crop-water-requirement assessments. The framework is then demonstrated using the Meki catchment in Ethiopia's Central Rift Valley, a smallholder irrigation expansion hotspot where uncoordinated surface and groundwater use has begun to generate seasonal water conflict and resource stress. The case study draws on coupled surface water-groundwater modelling, satellite-based irrigated area mapping, conjunctive water use assessment, and a multi-stakeholder policy dialogue.

The Meki catchment study shows that the highest irrigation water demand occurs in January and February when river flows are the lowest, making the timing and spatial distribution of water the major constraint for irrigation development in the catchment. Surface water deficit can be supplemented by groundwater in locations where both resources are available. In the upstream areas groundwater use is not likely and therefore demand management, improved efficiency and storage, can alleviate unmet water demands.

The guideline closes with technical and policy recommendations for practitioners, researchers and government agencies, emphasizing monitoring, enforceable allocation rules, institutional cross-sector and upstream–downstream coordination, locally appropriate demand management and local technical capacity building.

## 1. Introduction: Why conjunctive use matters

Sub-Saharan Africa (SSA) grapples with growing population that requires food security while the changing climate puts pressure on food production due to unreliable rainfall for a region that massively depends on rainfed agriculture. Irrigation is viewed as an important strategy to improve food security and protect rural livelihoods (Balasubramanya and Lele, 2022). In addition to large-scale irrigation, smallholder irrigation was found to considerably contribute to agricultural productivity growth in SSA (Xie et al., 2013). However, only 4% of arable land in SSA is irrigated as per Mwamakamba et al., (2017) and expanding such irrigation in most places was limited by water scarcity (Xie et al., 2013). In other cases, expanding irrigation is causing water scarcity and leading to seasonal drying of rivers and localized conflicts among water users (e.g., Taye et al., 2026).

In locations where both surface and groundwater are available, considering conjunctive use of these resources will support the sustainability of water resources. Conjunctive water use has gained global attention in many parts of the world, where the consensus has been that it has the potential to meet the increasing demands of competing water users (WRC, 2022). However, its application in SSA counties is limited with some efforts of integrating groundwater to ease challenges of surface water in Southern Africa (e.g. Botswana and South Africa).

There are many definitions of conjunctive water use. In the context of this guideline, conjunctive water use is defined as the coordinated use of surface and groundwater to maintain a continuous water supply for domestic, agriculture, or industries of a region over a long term (Blomquist et al., 2001). The coordination can be in space and time depending on resource availability to meet the increasing demands from different sectors of society for water (WRC, 2023). When surface water is insufficient or unreliable groundwater can supplement surface water. In the case of irrigated agriculture, conjunctive use refers to the strategic, coordinated combination of surface water and groundwater to optimize irrigation supply while minimizing the drawbacks of relying on either source alone that can lead to depletion of the resources.

Conjunctive use can be passively managed where farmers simply switch between sources, using groundwater in dry years or dry seasons and surface water when it is available, or actively managed, through deliberate measures such as Managed Aquifer Recharge, MAR (Dillon et al., 2019) or coordinated use of the two water sources. Hence, conjunctive use is not simply using both sources, but it's planned and coordinated use of both sources to achieve a better irrigation outcome without depleting either of the water resources (Singh, 2014). While the benefits of conjunctive water use have been recognized for a long time, there is limited guidance on how to use these resources for African catchments that are mostly dominated by smallholder farmers such as in Ethiopia.

**Box 1: What is conjunctive water use?**

- **Definition:** the coordinated use of surface and groundwater, in space and time, to keep a reliable water supply over the long term without depleting either source (Blomquist et al., 2001).
- **Passive conjunctive use:** use of surface and groundwater sources without coordination such as farmers switching from rivers to groundwater wells when rivers run dry.
- **Active (managed) conjunctive use:** surface and groundwater sources are deliberately planned to be used together, for example through allocation rules, seasonal schedules or managed aquifer recharge.
- **This guideline** focuses on the information needed to move from passive to planned conjunctive use in smallholder irrigation setting in Ethiopia.

## About this guideline

### Purpose

This guideline is the first attempt to respond to the existing information gap on how to implement conjunctive use in smallholder irrigation in Ethiopia noting that most of the global practice is focused on managed aquifer recharge. The guideline covers why conjunctive use matters, how to assess it, and how it works in practice within the realities of farmers in Ethiopia with fragmented land and dynamic food production practices.

### Intended users

This guideline is intended for:

- Basin development offices and regional water bureaus, which allocate water, issue abstraction permits and monitor water resources.
- Woreda[1] agriculture, irrigation and water offices advise farmers, coordinate irrigation schedules, plan seasonal irrigation and map irrigated areas.
- Irrigation planners, consultants and researchers, who carry out water resources assessments and modelling.
- Policy makers, who set up coordination, regulation and investment in irrigation and water management.

### Scope

The guideline focuses on the assessment and planning: how much surface and groundwater are available, how much is needed for irrigation, and how the two resources are combined to meet irrigation demand without depleting either. It does not cover water quality, the choice of pumping technology (either diesel or solar), or detailed social, economic and legal aspects, although these are important when conjunctive use is put into practice.

### Technical knowledge requirements

To use this guideline effectively, users should have a working knowledge of:

- Hydrological principles, including catchment water balance, rainfall-runoff processes and flow regime characteristics.
- Hydro-meteorological data analysis, including time series analysis, gap filling and statistical tests for consistency and homogeneity.
- Hydrological and groundwater modelling, including model setup, calibration, validation and performance evaluation.
- Geographic information systems (GIS) and remote sensing, for catchment delineation, land cover classification and irrigated area mapping.
- Crop water requirement estimation, including the Food and Agriculture Organization (FAO)-56 approach and other tools.
- Basic concepts of environmental flows and flow regime alteration.

Users are not expected to be specialists in all these areas. Where advanced data analysis, hydrological or groundwater modelling, or other specialized assessments are required, support from qualified technical experts may be necessary. Basin authorities, regional water bureaus,

[1] woreda is the third-level administrative unit in Ethiopia, similar to a district. It is a local government unit.

and woreda experts can use the guideline to understand the assessment process, interpret the results, and apply the findings to conjunctive surface water and groundwater management.

**How to use this guideline**

This guideline is organized to take users from the rationale for conjunctive water use through to its practical application.

Section 1 introduces conjunctive use of surface and groundwater, explains why it matters, and describes the purpose, intended users and scope of this guideline.

Section 2 presents the assessment framework for conjunctive water use. It explains the following steps (1) irrigated area estimation, (2) irrigation water demand estimation, (3) water resources availability estimation, and (4) conjunctive water use assessment. Each step describes the data, methods and tools needed.

Section 3 demonstrates the framework in the Meki catchment, showing how each step was applied, the key findings, and lessons.

Readers may use this guideline in different ways depending on their needs. Planners and decision-makers may focus on Section 1 and the key findings and lessons in Section 3. Technical staff and modelers may go directly to Section 2 for the step-by-step methods and use Section 3 as an example of the framework demonstration.

## 2. Framework for conjunctive water use assessment

Assessing and planning conjunctive use of water for irrigation requires information on: (1) how much water is physically available from both surface and groundwater in a catchment, (2) how much irrigated area currently exists and where, and how much it could sustainably expand to in the future, (3) how much water is needed for meeting irrigation water demand at present and in the future, (4) which irrigation areas use surface water and which ones use groundwater, and (5) what is the sustainability limit of abstraction from these water sources. Such information provides a catchment-scale water balance check that shows water availability and whether current or planned irrigation is sustainable and the conditions needed for attaining sustainability. The conjunctive use of water for irrigation can be assessed using the methodological framework given in Figure 1. This framework focuses on the quantity of water to avoid depletion of aquifers and degrading ecosystems.

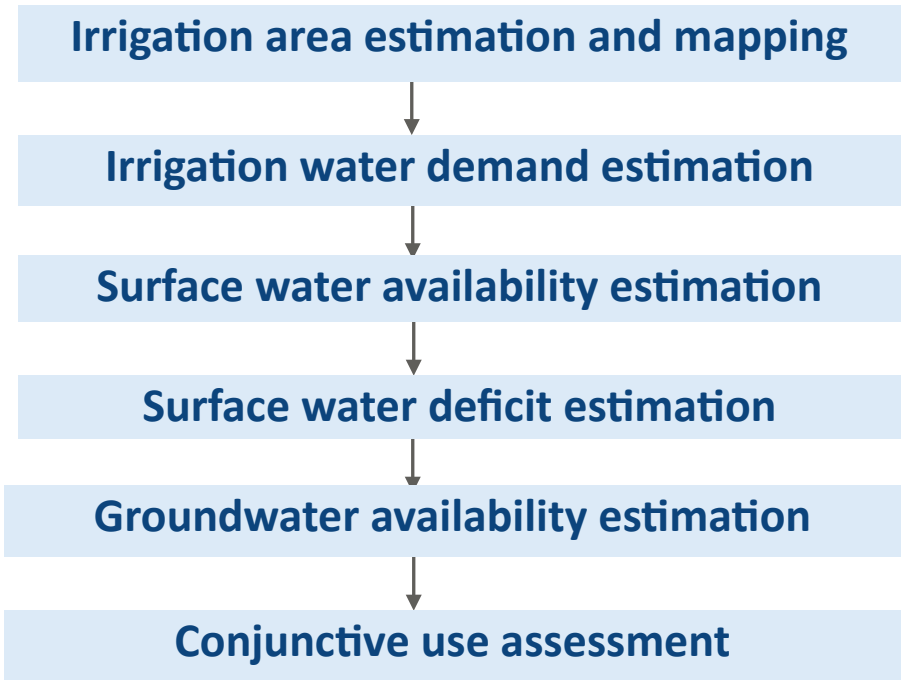



*Figure 1: Proposed methodological framework to guide assessment of conjunctive use of water for irrigation*

## Step 1: Irrigated area estimation

Having accurate information on the irrigated area per season is critical to properly manage the amount of water required for irrigation as competition for water among agriculture, domestic supply, industry, livestock, energy production, and environmental needs increases. There are two approaches to estimate actual irrigated area. These are (a) ground-based and (b) remote sensing-based methods.

Ground-based methods include surveying farmers' landholdings, cadastral or administrative records, or a single time-based survey of irrigated lands. This is commonly done by local government bodies with agriculture, irrigation experts of districts or extension agents. The ground-based methods are useful since they provide actual on the ground information. However, the information may be outdated, incomplete, and repeated surveys can be logistically cumbersome and expensive. These limitations lead to the adoption of the second method.

Remote sensing-based irrigated area estimation is becoming more common as earth observation (EO) data are becoming more accessible. EO can provide spatially continuous information over large areas and multitemporal information based on the revisit time of different satellites. The availability of multi-temporal information is useful for regularly updating and capturing the changes in irrigation activity. Examples of open-source satellite imagery that can be used in irrigated area assessment can be obtained from Landsat and Sentinel-2 missions. Landsat has the world's longest continuous data record of our earth's surface, extending back to 1972 that is useful to understand gradual environmental changes and sudden disturbances across local, regional, and global scales spanning over multiple decades. Landsat imagery offers a 30 m horizontal resolution (EROS, 2020). In comparison, Sentinel-2 provides higher resolution imagery at 10 m for selected bands, enabling more detailed identification and differentiation of vegetation, cropland, bare soil, water, built-up areas, and other land-cover types (Drusch et al., 2012) but provides shorter time coverage starting 2015. There are two approaches for mapping irrigated areas using Remote sensing (a) vegetation indices and (b) machine learning approach.

### Vegetation indices

Vegetation indices derived from satellite images can be used for mapping irrigated areas. Examples include the Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1974) and the Enhanced Vegetation Index (EVI) (Huete et al., 2002). NDVI establish a value for how green an area is, which demonstrates the quantity of vegetation present in a given area and its state of health or vigor of growth. EVI is an optimized remote-sensing satellite index used to quantify green leaf vegetation, improve sensitivity in high-biomass regions, and reduce background noise compared to the standard NDVI.

### Machine learning approach for classification and mapping

Various supervised machine-learning algorithms (random forest, support vector machine or deep learning models like Long Short-Term Memory (LSTM) can be used to map irrigated areas by integrating multi-sensor EO data, vegetation indices, multi-temporal satellite observations, and climate information (e.g. rainfall) with reference samples of irrigated and non-irrigated land. By integrating information on seasonal vegetation dynamics, surface moisture conditions, crop characteristics, and climatic variability, the model can distinguish irrigated from non-irrigated areas and identify their irrigation status during specific observation periods (Tadesse et al., 2026).

When applying remote-sensing methods to map irrigated areas, it is important to first mask non-cropland areas using an up-to-date land-use/land-cover map. This helps restrict the analysis to agricultural areas and reduces misclassification caused by non-agricultural surfaces.

After the irrigated area map is produced it is also important to validate against ground-truth points using Global Positioning System (GPS) located field survey and engaging government institutions at local levels. Such validated map can be useful for planning purposes if it is accepted by local authorities based on their on-the-ground experience.

**Box 2: Steps for irrigated area mapping using EO data**

1. Obtain an up-to-date land use/land cover map or classify one from recent imagery and create a cropland mask.
2. Create monthly composite multi-sensor satellite imagery covering the dry season, compute vegetation indices, and rainfall data.
3. Collect reference training samples of irrigated and non-irrigated agricultural areas through visual interpretation of monthly Sentinel-2 composite images, supported by ground-truth data collected through GPS-based field surveys and high-resolution imagery from Google Earth and Esri basemaps that corresponds to observation period.
4. Within the cropland mask, separate irrigated land from rainfed cropland, using vegetation indices (NDVI or EVI) with dry-season thresholds derived from training data, or by training LSTM model.
5. Carryout classification performance assessments using appropriate metrics.
6. Review the resulting irrigation map with local agricultural and irrigation offices to verify its consistency with local conditions and apply post-classification processing to correct errors and improve the spatial consistency of the final map.
7. Classify irrigated plots by likely water source (surface water, groundwater or both), based on their location relative to rivers and diversion schemes, and verify the classification with local experts.
8. Summarize the irrigated area by water source for each sub-catchment.

## Step 2: Irrigated water demand estimation

Once the irrigated area extent is identified the next step is to determine the amount of water needed to irrigate a certain crop in that area. Two approaches can be applied to estimate crop water requirements (CWR): (i) an assessment based on the FAO-56 methodology (Smith, 1992) and (ii) a remote sensing approach using actual evapotranspiration (ETa) derived from Landsat imagery.

CWR assessment is commonly conducted using the dominant crops in catchment using the CROPWAT software of FAO. The dominant crop with the maximum water use requirement can be used as necessary to estimate the maximum water demand. The reference crop evapotranspiration (ETo) is estimated by the FAO Penman-Monteith method (Allen et al., 1998). It uses climate data such as temperature, humidity, wind speed and solar radiation. For specific crops, the crop evapotranspiration (ETc) is determined by multiplying ETo by the crop coefficient (Kc) of specific growth stages (Allen et al., 1998). The net irrigation requirement subtracts effective rainfall (Pe) from ETc, and the gross irrigation water requirement (GIR) further accounts for conveyance and field-application efficiency losses. Effective rainfall can be estimated using the FAO-recommended United States Department of Agriculture (USDA) Soil Conservation Service method (Smith, 1992).

The second approach is based on satellite-derived actual evapotranspiration (ETa) that can be used as a proxy for crop water requirements. This approach provides daily estimates at 30 m spatial resolution that uses Landsat images. ETa is commonly derived from Landsat imagery using the Operational Simplified Surface Energy Balance (SSEBop) model (Senay et al., 2013, 2022). Processed images can be requested from the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center's Science Processing Architecture (ESPA). This can be requested on-demand platform without running the model directly on one's local machine. SSEBop combines land surface temperature from Landsat with meteorological data to estimate ETa.

With this method one should first define the area of interest, such as the scheme, command area or field boundaries, and the analysis period, typically the cropping season. SSEBop ETa images for that area and period are then ordered through ESPA, and images affected by cloud cover are removed or flagged. Daily ETa values are extracted for the area of interest and summed to estimate seasonal crop water use. Where possible, these results are compared with field-based, or FAO-56 crop water requirement estimates. Because ETa reflects the water actually consumed by the crop rather than its full demand, it may underestimate crop water requirements where crops are water-stressed or under-irrigated. ETa is also a net, consumptive quantity, so it should not be compared directly with the gross irrigation requirement.

To make the two comparable, effective rainfall is first subtracted from seasonal ETa to provide the irrigation water that is actually consumed. This value is then compared with the net irrigation requirement. Where measured diversions or field applications are available, dividing consumed irrigation water by the volume applied gives an estimate of actual irrigation efficiency (consumed fraction). Otherwise, an assumed efficiency for the irrigation method can be used to convert ETa-based consumption into an estimate of gross water delivered. Not all non-consumed water is lost, however, as part of it returns to the system as return flow or groundwater recharge. In addition, Landsat revisits a site only every 8–16 days, so daily values between overpasses are interpolated and need careful checking during cloudy periods. For these reasons, this approach is best used alongside field-based estimates, not as a replacement for them.

In smallholder irrigation systems, the FAO-56 approach is generally more appropriate than remotely sensed ETa for estimating crop water requirements at farm or plot level. Smallholder plots are often smaller than or comparable to the spatial resolution of available remote sensing products (30 m for Landsat-based SSEBop and coarser for MODIS-based products, 500m).

As a result, satellite pixels frequently mix irrigated crops with bunds, trees, fallow land or neighboring fields, which makes plot-level ETa estimates unreliable. FAO-56, by contrast, does not depend on plot size and needs only weather data, crop type, planting dates and growth-stage information, which can be applied readily through tools such as CROPWAT.

**Box 3: Steps for estimating irrigation water demand by sub-watershed and water source using FAO-56 approach**

1. Identify the dominant crops in irrigated areas. Use the crop with the highest irrigation water requirement to estimate peak water demand.
2. Calculate reference evapotranspiration (ETo) with the FAO Penman-Monteith method using climatic data.
3. Obtain crop evapotranspiration (ETc) by applying ETo with the crop coefficient (Kc) for each growth stage.
4. Estimate the net irrigation requirement (CWR) by subtracting effective rainfall from ETc.
5. Apply irrigation efficiency to CWR to obtain gross irrigation requirement (GIR).
6. Divide the catchment into sub-catchment relevant for estimating spatially detailed irrigation demands and water availability.
7. Classify the irrigated area assigned to each sub-catchment by water source: surface water (SW), groundwater (GW), or both (SW+GW).
8. Overlay the irrigated area map on the sub-catchment boundaries and assign the water source to each irrigated area. For example, if a diversion in sub-catchment 6 (Figure 1) supplies a command area in sub-catchment 8, count that area and its water demand under sub-catchment 6, because the water is taken from sub-catchment 6.
9. Convert GIR from a depth unit to volume estimates for each sub-catchment.
10. Sum across water sources to obtain the total irrigation demand for each sub-catchment, followed by aggregation across sub-catchments to the catchment scale total irrigation demand.

# Step 3: Water resources estimation

## Assessing hydro-meteorological data

Hydro-meteorological data are the foundation of both surface water and groundwater assessments. In some catchments, long and good-quality records are available; in others, data are sparse, short or of uncertain quality. The quality of the data determines which methods can be used and how much confidence can be placed in the results. Before setting up any model, assess the data as described in Box 4:

**Box 4: Steps for assessing hydro-meteorological data availability, adequacy and quality**

1. Define data requirements. Identify the variables, spatial coverage, temporal resolution and required period of analysis.
2. Compile data inventory. Gather available climatic, hydrological, and infrastructure data records from relevant institutes and document each station's location, elevation, record length, resolution and custodian.
3. Assess spatial coverage. Map the stations and check whether they represent the main climatic and topographic zones and key diversion or outlet locations.
4. Assess temporal adequacy. Review record length, continuity, resolution and overlap between stations for calibration, validation and gap filling.
5. Assess data quality. Examine missing values, consistency, homogeneity, outliers and errors; also review streamflow rating curves.

6. Determine fitness for purpose. Classify each dataset as usable, usable after correction or unsuitable for the intended assessment. In cases of inadequate data, decide which alternative sources or methods can be used.
7. Address gaps and limitations. Apply appropriate gap-filling methods or use bias-corrected satellite and reanalysis products where observations are inadequate.
8. Document uncertainties. Record all data sources, quality control procedures, gap-filling methods, corrections, assumptions, exclusions and remaining limitations.

Once the water demand for irrigation is established the next step is to determine the amount of water available in a catchment. In catchments where there is distinct seasonal rainfall, using irrigation in the dry season is dependent on water resources availability and accessibility from surface and groundwater sources. Understanding the baseline water resources is important to plan irrigation development in the current and future periods. This requires assessing the surface and groundwater system under existing or naturalized conditions.

## Surface water estimation

Surface water is commonly assessed by estimating catchment water balance through hydrological modelling. Hydrological models such as the Soil and Water Assessment Tool (SWAT) can simulate rainfall-runoff processes based on Digital Elevation Model (DEM), land use and soil maps and climatic inputs. Hydrologic Response Units (HRUs) are generated from combination of land use, soil and slope to provide spatial basis for representing key hydrological processes. The models should be calibrated and validated against observed streamflow at available gauging stations in the catchment. The model needs to be calibrated against streamflow that is not affected by human interventions, such as diversions or pumping, so that it simulates naturalized flow. Such models can generate naturalized flow series representing the catchment characteristics before water users or developmental projects are in place to consume the water. The spatial configuration of the model can be set up in such a way that it includes major surface-water diversion sites and detailed sub-catchments where spatially detailed irrigation demands can be estimated.

The calibrated and validated hydrological model can be used for assessing various baseline conditions and potential scenarios of surface water. This includes seasonal or inter-annual surface flow amount estimation under current and projected climate, with current and increasing irrigation area, and land use change. This will provide the baseline surface water availability from which farmlands can use water for irrigation and the potential changes based on assessed scenarios.

For the existing condition, once the supply and demand are estimated, the surface-water supply can be compared with irrigation water demand in each sub-catchment to quantify surface-water deficits for irrigation. Care should be given to delineating sub-catchment using the major diversion sites as outlet points, so that the estimated supply reflects the water available where it is abstracted for irrigation. The results will identify sub-catchments where surface water is sufficient to meet irrigation demand and sub-catchments where water deficits can occur. Where surface-water availability is insufficient, groundwater can be considered as a complementary source or depending on the location and availability, it can be the main source for irrigation.

**Box 5: Steps for estimating surface water availability with the SWAT model**

1. Prepare input data:
    a. Spatial data - Digital Elevation Model, land use and soil maps,
    b. Time-series climatic data - Rainfall, maximum and minimum temperature are the minimum requirements. Include humidity, wind speed and solar radiation if available.
    c. Time-series hydrological data - Collect observed streamflow data from available gauging stations and the locations of the major irrigation water diversion sites.
2. Set up the SWAT model for the catchment. Use the major diversion sites as outlet points during sub-catchments delineation. Use the same sub-catchments as in the irrigation demand estimate.
3. Calibrate the model against observed streamflow for a selected period and validate it with a separate period. Allow initial warm-up period of at least 2–3 years. Tools such as SWAT-CUP can be used for calibration. The calibration and Validation should be done for period where there is no significant development
4. Run the model to simulate naturalized flow, which is the streamflow before water is taken for irrigation or other uses. Estimate the surface water availability for each sub-catchment by month and season.
5. Compare the available surface water with the irrigation demand in each sub-catchment to find the surface water deficit sub-catchments.
6. Map the sub-catchments with enough surface water and those with a deficit. Where there is a surface water deficit, groundwater can be a supplemental source if available in the sub-catchment.

## Groundwater estimation

Groundwater availability for irrigation is mostly from shallow groundwater systems, especially for smallholder irrigation. Understanding the recharge and storage of groundwater is an important aspect to use the resource sustainably. This requires water-table monitoring networks and numerical groundwater flow models such as Modular Hydrologic Model (MODFLOW) to estimate groundwater availability. A numerical groundwater model can be set up to quantify spatiotemporal interactions between the aquifer system and surface water bodies. Such a model can simulate various pumping and recharge scenarios to determine the catchment's safe yield from the groundwater wells and the aquifer's storage capacity. Such assessment will ensure conjunctive use strategies can maximize water availability while preventing declines in water levels.

The first step in groundwater modeling is to develop a conceptual model of the groundwater flow system. The conceptual model brings together available hydrogeological and hydrological data, presented as maps, cross-sections or tables, to describe the extent, thickness and properties of each aquifer and confining unit.

The groundwater flow system is commonly modelled using MODFLOW. Unlike the SWAT model the MODFLOW simulates in grids, and the model domain is commonly discretized into a uniform horizontal grid size. The model can be divided into vertical layers depending on aquifer lithology. Existing groundwater pumping wells should be added to the model when the model is set up to represent groundwater pumping from the shallow aquifer.

To estimate aquifer properties, the MODFLOW model should be calibrated in two stages. First, the steady-state model is calibrated against average static water levels measured in wells distributed across the study area. Second, the transient model is calibrated against time-series water level data, using the simulated water levels from the calibrated steady-state model as its initial conditions.

**Box 6: Steps for estimating groundwater availability using MODFLOW**

1. Develop a conceptual model by defining the model domain, aquifer layers, recharge, pumping situation, and boundary conditions
2. Discretize the model domain into a horizontal grid and vertical layers
3. Assign initial aquifer properties (hydraulic conductivity, specific yield and specific storage) by hydrogeological zone, using pumping test data and literature values
4. Add hydrological stresses
5. Calibrate steady-state model against static water levels
6. Calibrate transient model against time series of water levels using steady sate water level as initial condition
7. Evaluate calibration statistics, the spatial distribution of residuals and the water balance error, which should be below 1%
8. Run pumping and recharge scenarios to estimate how much groundwater can be sustainably abstracted to meet surface water deficits.

## Step 4: Conjunctive water use assessment

From various approaches presented in this guideline, we present two of them to assess the feasibility of conjunctive use of surface and groundwater. In the first approach (Box 5), the irrigation water requirement of the irrigated area in each sub-catchment can be compared with available surface water simulated using a hydrological model like SWAT, and the resulting deficit is assumed to be met from groundwater. This deficit can be distributed among a defined number of supplementary wells, and the resulting pumping rates are entered into the MODFLOW for each stress period. The pumping rates are therefore prescribed: they do not change in response to simulated conditions such as streamflow, soil moisture, or groundwater levels during the model run. This approach is simple, transparent, and requires relatively little data, which makes it suitable for initial assessments and scenario screening. However, it does not account for return flows from irrigation or for feedback between groundwater pumping and surface water availability, for example where pumping reduces streamflow and thereby increases the surface water deficit.

The second approach is using MODFLOW Newton-Raphson formulation (NWT)'s Agricultural Water Use (AG) Package, which simulates the conjunctive use of surface water and groundwater by automatically pumping groundwater whenever surface water availability falls short of demand. The approach links irrigated fields to surface water diversions and to supplemental wells. Surface water diversions are used first, and groundwater pumping is applied only when diverted surface water is insufficient to meet the demand, subject to the maximum capacity of each well. Applied irrigation water infiltrates through the unsaturated zone, so return flows to the aquifer are represented. Because pumping is computed dynamically, it responds to simulated streamflow and climatic conditions, increasing in dry periods and decreasing when surface water is plentiful. This provides a more physically consistent representation of conjunctive surface water and groundwater use, but it requires more input data such as crop coefficients, field areas, diversion points, and well capacities and more effort in model setup and calibration.

The first approach simulates the impact of a pre-defined pumping scenario, whereas the second simulates pumping as an outcome of the interaction between crop water demand, surface water availability, and groundwater. The first approach (Box 7a) is recommended where data are limited or where the aim is to test the impact of specified abstraction rates. The second approach (Box 7b) is recommended where the aim is to represent conjunctive use realistically, assess how supplemental pumping varies with climate and streamflow, or evaluate feedback between groundwater abstraction and surface water resources.

**Box 7a: Steps for conjunctive water use assessment – first approach**

SWAT can be used as a diagnostic tool to show where and when river flow is not enough to meet irrigation demand. This surface water deficit shows where groundwater may be needed to supplement.

1. Monthly river flow can be simulated with a calibrated SWAT model for each sub-catchment. Long-term mean monthly flow can then be converted to monthly water volumes ($m^3$) for the irrigation season
2. Irrigated areas can be grouped by their likely water source: surface water, mixed (surface and groundwater), or groundwater. Each area can be assigned to the sub-catchment from which it takes water
3. The gross irrigation requirement can be obtained by dividing the crop's net irrigation requirement by irrigation efficiency. Monthly demand can then be calculated as irrigated area × gross requirement
4. Water availability can be calculated in order from upstream to downstream sub-catchments. In each sub-catchment, available water is the flow generated within that sub-catchment (from SWAT) plus any flow left over from the sub-catchments upstream. This water can be allocated first to areas irrigated by surface water and then to mixed-source areas, with any remaining flow passed downstream. Areas irrigated only from groundwater are not included in this step
5. The deficit can be calculated as demand minus allocated river water, first for irrigated areas likely supplied by surface water, and then for irrigated areas likely supplied by both surface water and groundwater, using the water left after the first group has been supplied. The two deficits can then be summed for each sub-catchment and month. The result is the irrigation demand that river water cannot meet, which would need to be supplied from groundwater
6. The deficit can be compared with the available groundwater in each sub-catchment to assess whether it can be met from groundwater
7. Distribute the surface water deficit to the number of supplementary wells in each sub-catchment and determine pumping rate of individual supplementary wells
8. Run MODFLOW with pumping rate determined in step 7
9. Evaluate the effect of pumping on groundwater levels, baseflow, and downstream flows

*Note: environmental flow requirements were not considered, so the estimated deficit is a lower bound.*

**Box 7b: Steps for conjunctive water use assessment – second approach**

1. Develop a MODFLOW model that uses SWAT-simulated recharge and the sum of surface runoff and lateral flow in each subbasin as inflow to the streams. The model should include the Streamflow-Routing (SFR) Package so that conjunctive use of surface water and groundwater can be simulated.
2. Add a diversion point at the outlet of each SWAT subbasin, represented as a diversion segment in the SFR Package. This allows the model to simulate how much water can be diverted from each stream segment to satisfy irrigation demand.
3. Calculate the total irrigation water demand for each subbasin by dividing the crop irrigation water requirement by the assumed irrigation efficiency. Assign this demand to the corresponding SFR diversion point as the diversion rate.
4. Using the map of irrigated area by source type, calculate the total irrigation volume for areas irrigated only with groundwater. Divide this volume equally among the groundwater-only irrigation wells to obtain the pumping rate for each well. Simulate these wells with the standard Well (WEL) Package, in the same way as the existing wells. Only conjunctive-use wells are simulated in the AG Package.

5. For each SWAT subbasin, map the conjunctive use irrigated area to the corresponding MODFLOW cells so that irrigation water from each diversion can be applied to the correct cells in the AG Package
6. Link the irrigated cells in each subbasin to their sources of irrigation water in the AG Package: the SFR diversion segment for that subbasin and the supplemental groundwater wells. The wells supply any demand that cannot be met by surface-water diversions.
7. Run the model with the AG Package to simulate conjunctive use of surface water and groundwater. Because the AG Package is available only in MODFLOW-NWT, the model must be run with MODFLOW-NWT. During the simulation, the AG Package diverts surface water from the SFR segments first and automatically pumps the supplemental groundwater wells when the diversions cannot meet the irrigation demand

### Step 5: Sustainability limit for water abstraction

The amount of water that can be abstracted sustainably is limited by the need to keep enough flow in the river to maintain its ecological functions. There is no one universal method to determine the threshold to limit the abstraction of water from rivers and groundwater. Depending on the region and data availability situation different approaches can be used. The absence of comprehensive legal frameworks in places such as Ethiopia also hinders the operationalization of water allocation for environmental flows from rivers and groundwater wells. The most common approach to determine the threshold in data scarce situation is the Tennant method that sets environmental flow as a percentage of mean annual river flow (Tennant, 1976), which is commonly set as 15–20% of mean annual flow for downstream water requirement (Goshime et al. 2021). In the case of catchments with high seasonal variability like Ethiopia instead of the annual flow the monthly flow is used. Hence, the environmental flow can be specified as 20% of the mean monthly flow (e.g. Mekonnen et al. 2026).

For groundwater abstraction, UNESCO's groundwater sustainability indicators (Vrba et al., 2007) can be used. This indicator estimates the total annual groundwater abstraction as a percentage of mean annual recharge and is classified into three scenarios. The first scenario (Scenario 1) is when annual abstraction is below 90% of annual recharge, groundwater use is considered sustainable. The second scenario (Scenario 2) is when it is about 100% use has reached the limit of the resource. The last scenario (Scenario 3) is when groundwater use is above 100% the aquifer is over-exploited and its storage is being depleted. This approach is used to determine sustainability limits in the Meki catchment demonstration.

## 3. Demonstrating methodological framework: Meki catchment example

The methodological framework illustrated in the previous section was applied to the Meki catchment in Ethiopia where irrigation is expanding using both surface and groundwater sources. During dry season there are reports of rivers drying up and conflicts occurring among farmers on water use from surface water sources. Groundwater sources where available are being used considerably but with no reports of severe groundwater level decline or conflicts because of its use. Groundwater use is reported to be constrained less by physical scarcity than by the cost and access of pumping energy. This means that as solar-pump technology becomes cheaper and more widespread, groundwater abstraction is likely to expand quickly. Hence, the need to plan ahead on the sustainability of both surface and groundwater resources in the catchment.

## Meki catchment and irrigation development

The Meki Catchment lies within Ethiopia's Central Rift Valley and is one of the major drainage systems contributing inflow to Lake Ziway (Figure 2). The catchment is situated in central Ethiopia and extends across the administrative boundaries of the Central Ethiopia and Oromia Regional States. It lies between approximately 7°49′–8°29′N latitude and 38°13′–38°55′E longitude. The climate is semi-arid with average annual precipitation of 940 mm and the main rainy season being between July and September. The catchment's land use is predominantly cultivated land, accounting for 61% of the catchment area.

It is one of Ethiopia's smallholder irrigation hotspots, given its favorable terrain, rivers, lakes and shallow groundwater availability (Taye et al., 2022; 2026). Both surface water and groundwater are used for irrigation in the catchment. Surface water is commonly from river either using diversion scheme or direct pumping from the river while groundwater is from shallow wells and springs using motorized and, increasingly, solar-powered pumps. Shallow groundwater use is becoming increasingly important for food production and economic development in the region.

Water use for irrigation is largely uncoordinated between individual users and between upstream and downstream locations. Most of the upstream areas have surface water sources and the downstream area has flatlands that have ample groundwater sources. The dominant use of groundwater is the rift floor of the catchment. The catchment is also hydrologically important because agricultural water use within the Meki system is directly connected to downstream water availability and the broader water balance of the Lake Ziway system.

**Box 8: The Meki catchment briefly**

- **Location:** Central Rift Valley Lakes Basin, Ethiopia; drains into Lake Ziway. Passes through two regional states; the Central Ethiopia and Oromia
- **Area**: ~2,200 km², of which 61% is cultivated land
- **Climate:** semi-arid; mean annual rainfall about 910–940 mm, July–September main rainy season – Kiremt rains, February to May – shorter rainy season - Belg rains
- **Main irrigation water challenges:** rivers drying up in the dry season and upstream–downstream conflicts.

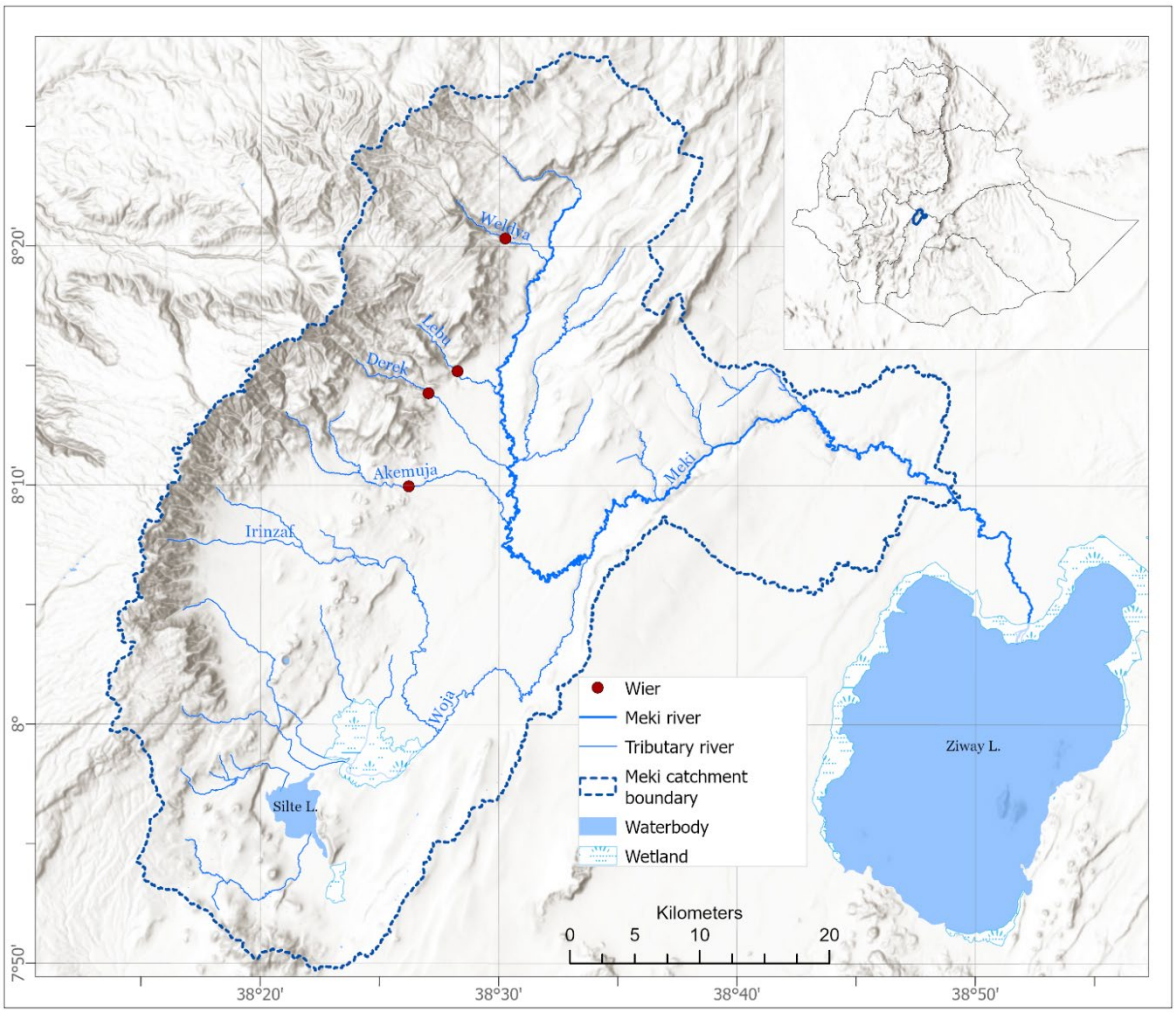



*Figure 2: Location of the Meki catchment in Ethiopia and the Rift Valley Lakes Basin. ARCPro GIS software is used to generate this map.*

## Step 1: Irrigation area mapping

In the case of Meki catchment, first, the actual irrigated area for a given dry season in 2024-2025 using EO data was mapped. This included Sentinel-2 imagery for land use/land cover (LULC) mapping, Sentinel-1 synthetic aperture radar (SAR) for complementary observations of crop structure and soil moisture, precipitation data from Climate Hazards Group InfraRed Precipitation with Station data- version 2, CHIRPS2 (Funk et al., 2015) for the climatic context needed to separate rainy season from dry season vegetation situation. The mapping followed three stages (Figure 3). First, LULC classification of the Sentinel-2 imagery produced a cropland mask, so that only cultivated land was analyzed further. Second, within this mask, an LSTM deep-learning model was applied to time series of these features to separate irrigated from rainfed cropland. An LSTM is well suited to this task because it learns from how observations change through the season, such as a crop that stays green after the rain has stopped, rather than from a single image. Third, LSTM-based irrigation area maps were validated through stakeholder consultations and field-level surveys. Field observations and local knowledge were used to verify mapped irrigation areas and identify discrepancies. The findings informed necessary refinements to produce the final irrigation area map.

The mapped irrigated plots were then classified by their likely water source based on their spatial relationship with river networks and diversion systems. Irrigation based on surface water sources mostly covers irrigated plots from river diversions. Irrigation based on

groundwater is irrigated plots where there are no river systems. Irrigated plots that are identified as irrigated areas from mixed sources are farms that are close to rivers within 500 m distance from the riverbanks. The irrigated area is then given by how much by source for each sub-catchment (Figure 4). In the 2024/25 dry season, 4,463 ha were irrigated in the catchment and out of this, 1,878 ha (42%) from groundwater, 1,344 ha (30%) from surface water and 1,241 ha (28%) from both sources (Figure 5).

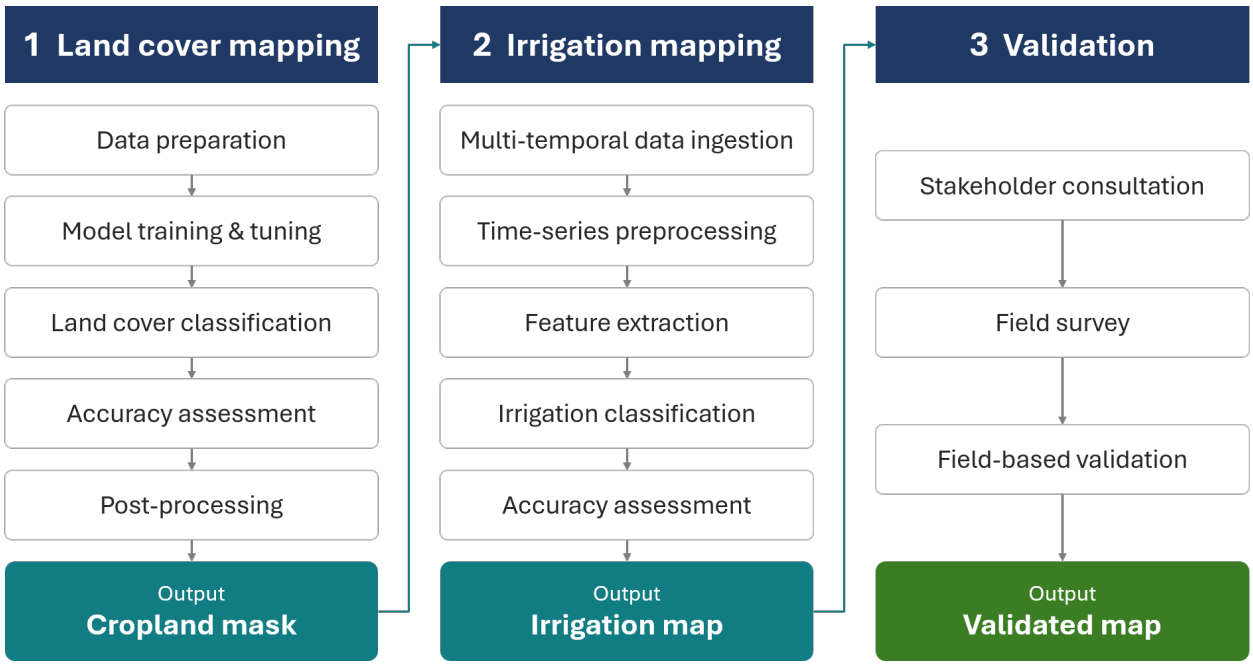



*Figure 3: Methodological workflow for mapping irrigated areas in the Meki catchment using Earth observation data, LSTM-based classification, and field validation*

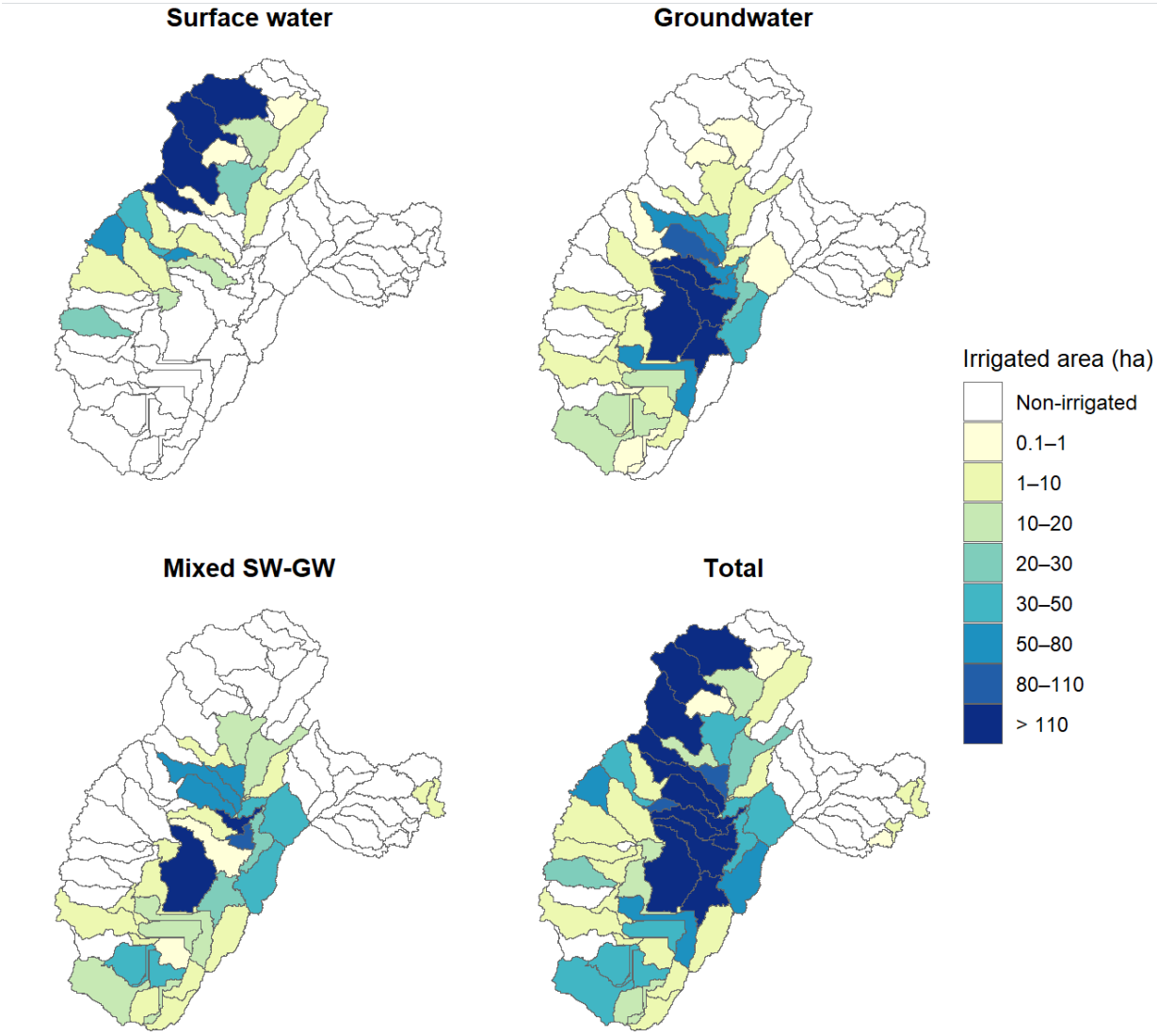



*Figure 4: Irrigated area per sub-catchment by source of irrigation water (surface water, groundwater, mixed surface water–groundwater) and for all water sources combined; dry season 2024/25. Sub-catchments in white indicate absence of irrigation.*

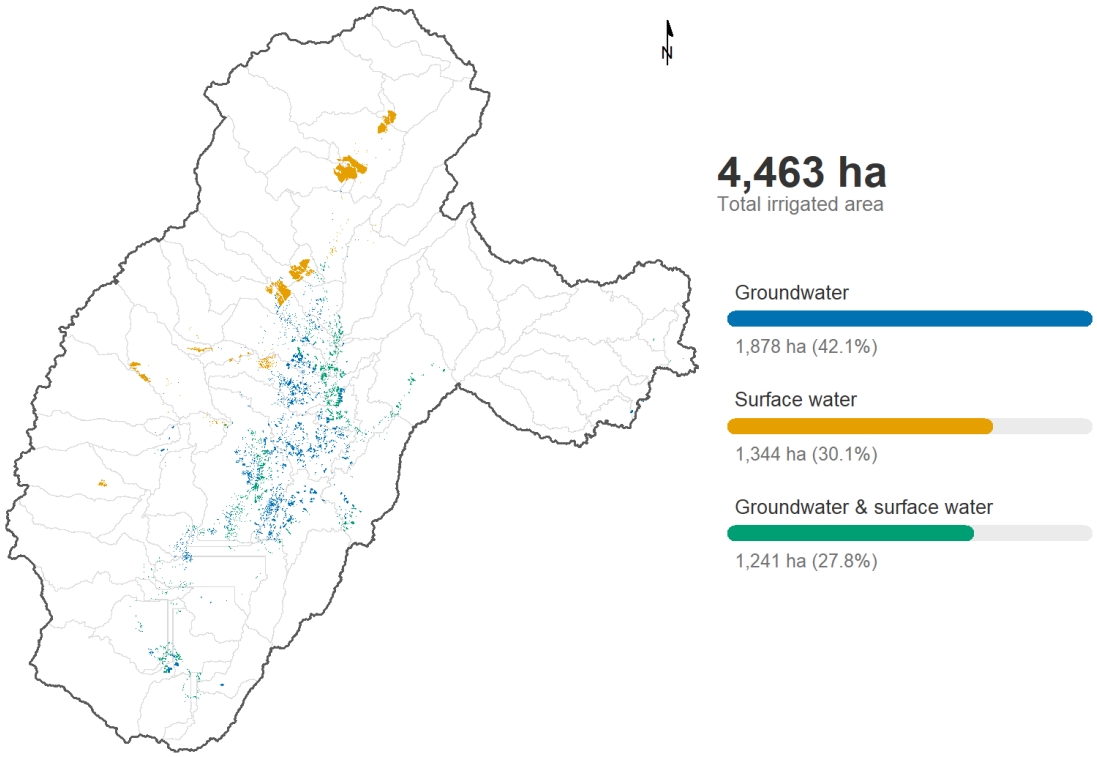



*Figure 5: Irrigated areas in the Meki catchment by source of irrigation water: surface water, groundwater, and mixed surface water and groundwater. Sub-catchments in white indicate absence of irrigated area.*

**Box 9: Key results – irrigated areas in the Meki catchment**

- **Total irrigated area:** 4,463 ha in the 2024/25 dry season
- **By water source:** groundwater 1,878 ha (42%), surface water 1,344 ha (30%), and both sources 1,241 ha (28%)
- **Spatial pattern:** surface water schemes are concentrated in the northern uplands, while groundwater and mixed-source irrigation dominate the rift floor
- **Implication:** groundwater is already central to dry-season irrigation, so its use needs to be planned and monitored with potential solar pumping expansion.

## Step 2: Irrigation water demand estimation

Water demand estimation was based on one of the dominant crops, tomato, with the aim of providing a conservative estimate of irrigation water demand. Although the tomato growing season in the area runs from December to April (Table 1), the analysis in this guideline covers December 2024 to March 2025, the period when crop water demand is highest and river flow is lowest. Tomato was selected because it is a dominant and relatively water-demanding dry-season crop. A single planting date was assumed for all plots to simplify the estimation.

Reference evapotranspiration was calculated using the FAO Penman–Monteith method using climatic data from the Ethiopian Meteorological Institute (EMI), while crop coefficients and growth-stage durations were obtained from Allen et al., (1998). Effective rainfall using the USDA Soil Conservation Service method was applied to estimate the CWR and an irrigation efficiency of 40% (0.40) was applied. The monthly irrigation water demand for each sub-

catchment was estimated by multiplying monthly gross irrigation demand per unit area by the irrigated area for each water-source category.

**Table 1: Monthly irrigation water requirement of tomato (mm)**

| Crop / parameter | Dec | Jan | Feb | Mar | Apr | Total |
|---|---|---|---|---|---|---|
| Tomato – irrigation requirement (mm) | 18.4 | 94.2 | 135.1 | 142.5 | 65.6 | **455.8** |
| Gross irrigation requirement, GIR (mm) | 46.0 | 235.5 | 337.8 | 356.3 | 164.0 | **1139.5** |

*Growing season: December–April. GIR = requirement ÷ irrigation efficiency (0.40). Analysis period (December–March): requirement 390.2 mm; GIR 975.5 mm. (Source: EEC,2024)*

Meki catchment's gross irrigation demand in the dry season of 2025 was 43.5 million m³. To show where this demand is likely to be met from, irrigated areas were grouped by their potential water source, areas likely supplied by groundwater, by surface water, or by both (mixed sources). On this basis, 18.3 million m³ (42%) of the demand falls in areas likely irrigated from groundwater, 13.1 million m³ (30%) from surface water irrigated areas and 12.1 million m³ (28%) from both sources (Figure 7). Because the same crop, and efficiency assumptions were used throughout, demand per hectare was assumed same everywhere (about 9,750 m³/ha), so differences between sub-catchments reflects the size of irrigated area only. The largest demands, more than 1 million m³ per sub-catchment, are in the northern surface water schemes and on the central rift floor (Figure 6). In total, 58% of the demand is expected to be met fully or partly from river's water.

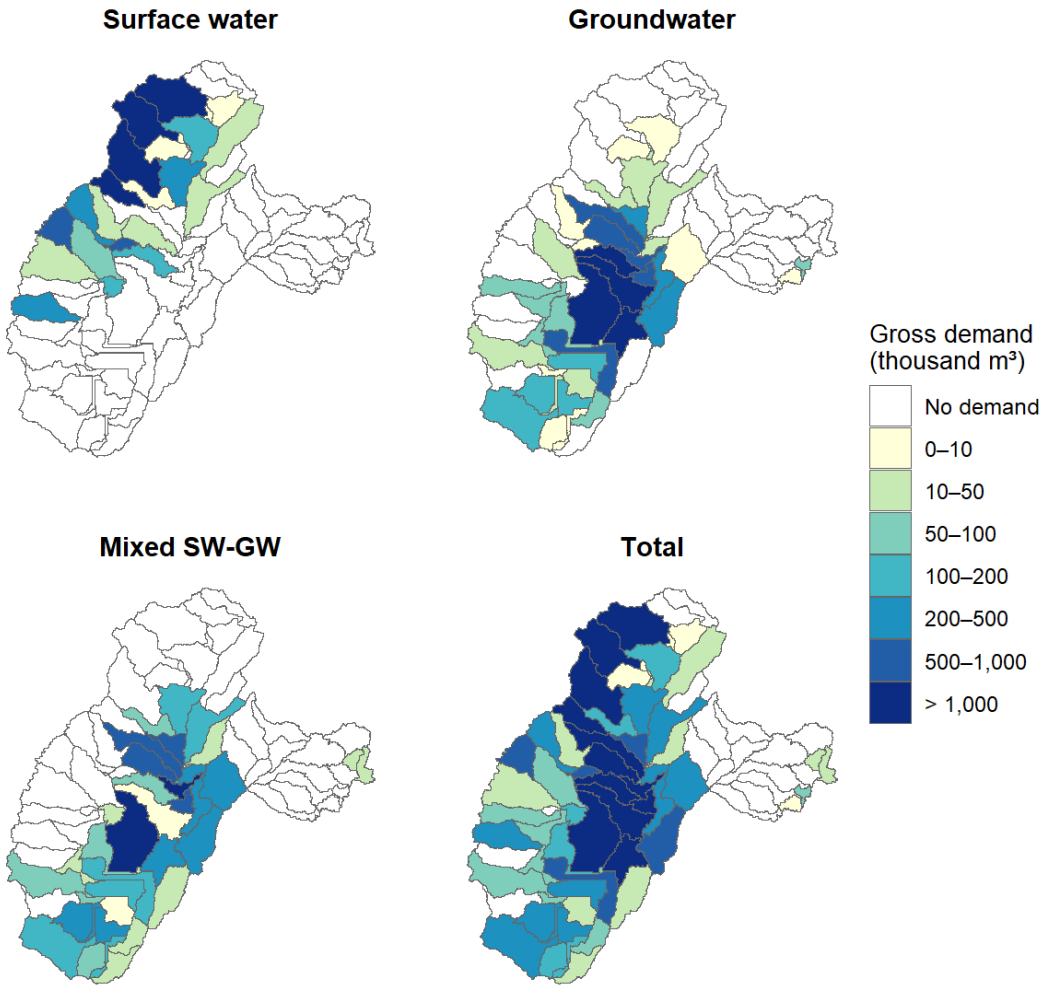



*Figure 6: Seasonal gross irrigation water demand per sub-catchment by source of irrigation water, Meki catchment, December 2024 – March 2025.*

Water demand rises steeply through the dry season, from 2.05 million m³ in December to 10.5 million m³ in January, 15.1 million m³ in February and 15.9 million m³ in March. February and March together account for 71% of the seasonal water demand. This peak occurs when river flow is lowest. The timing of water demand and water rather than the seasonal totals, therefore, determine whether surface water is sufficient and when groundwater is needed. It also points to demand-side options, such as staggering planting dates or growing crops with lower water use, which reduce demand in the critical months.

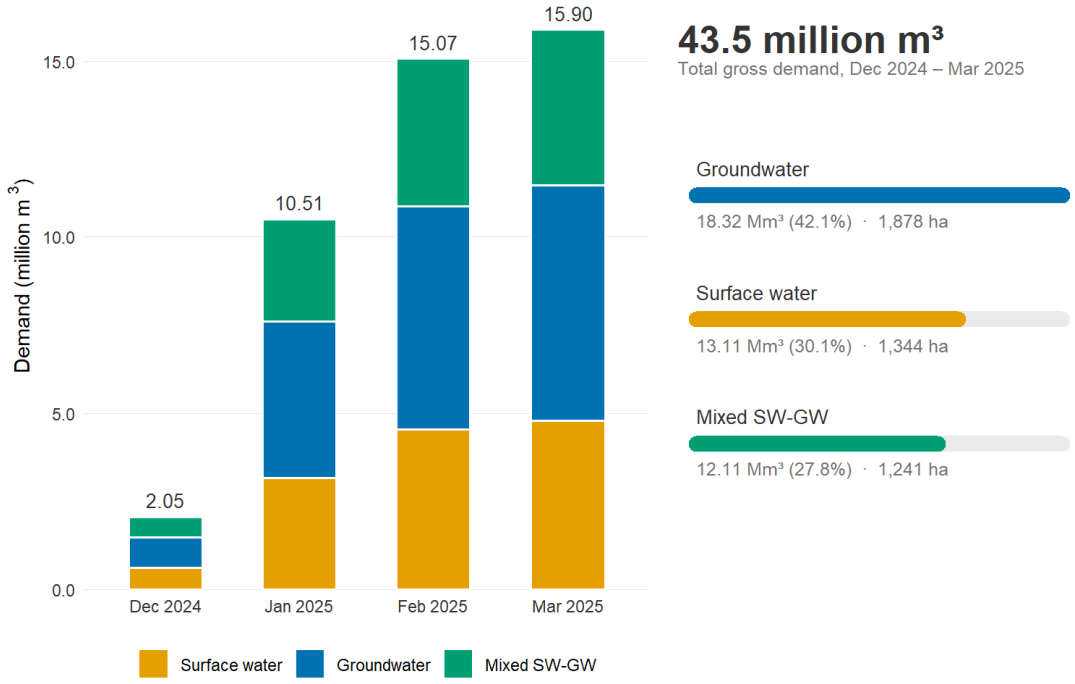



Figure 7: Dry-season gross irrigation demand (December 2024 - March 2025) by potential water source of the irrigated area: groundwater, surface water or mixed sources. Sources are inferred from irrigated farms' location, not from measured water abstractions

**Box 10: Key results – irrigation water demand**

- **Seasonal demand:** 43.5 million m³ (December 2024–March 2025), or about 9,750 m³/ha for tomato at 40% irrigation efficiency.
- **By water source:** 18.3 million m³ for groundwater source areas, 13.1 million m³ for surface water source areas and 12.1 million m³ for mixed-source areas; 58% of demand expected to be met from rivers.
- **Timing:** February and March account for 71% of seasonal water demand, when river flows are at their lowest.
- **Implication:** staggered planting dates, lower water-use crops and better irrigation efficiency can reduce demand in the critical months.

# Step 3: Water availability estimation

## Surface water availability estimation

SWAT was applied to the Meki catchment to simulate naturalized streamflow and assess the spatial and temporal availability of surface water. Naturalized streamflow represents the water generated by the catchment without accounting for existing surface-water abstractions and diversions. The SWAT model was set up using a 30-m Shuttle Radar Topography Mission (SRTM) DEM, the 2008 land use/land cover map, the Africa Soil Information Service (AfSIS) soil map, and climate data from CHIRPS and ERA5. The catchment was delineated into 81 sub-catchments, with major diversion sites considered during discretization to ensure that simulated streamflow represents water availability at key abstraction points. Model parameters were calibrated in SWAT-CUP (Abbaspour, 2015) against observed monthly streamflow at the

Meki gauging station for 1984–1991, and the model was validated for 1997–2000. The calibrated parameters are given in Annex Table 1. The reason for choosing this old dataset for calibration is to avoid impact of water resource development such as diversion on model calibration and validation. The model performed well with Nash-Sutcliffe Efficiency (NSE) of 0.75 for calibration and 0.63 for validation. Because NSE is dominated by high flows, low-flow performance was assessed separately using the logarithmic NSE (logNSE), which gave a value of 0.48 for the calibration period. The model reproduced the timing of the rainy-season peaks, and the near-zero dry-season flows, but underestimates some extreme peaks, such as from 1993 and 1994.

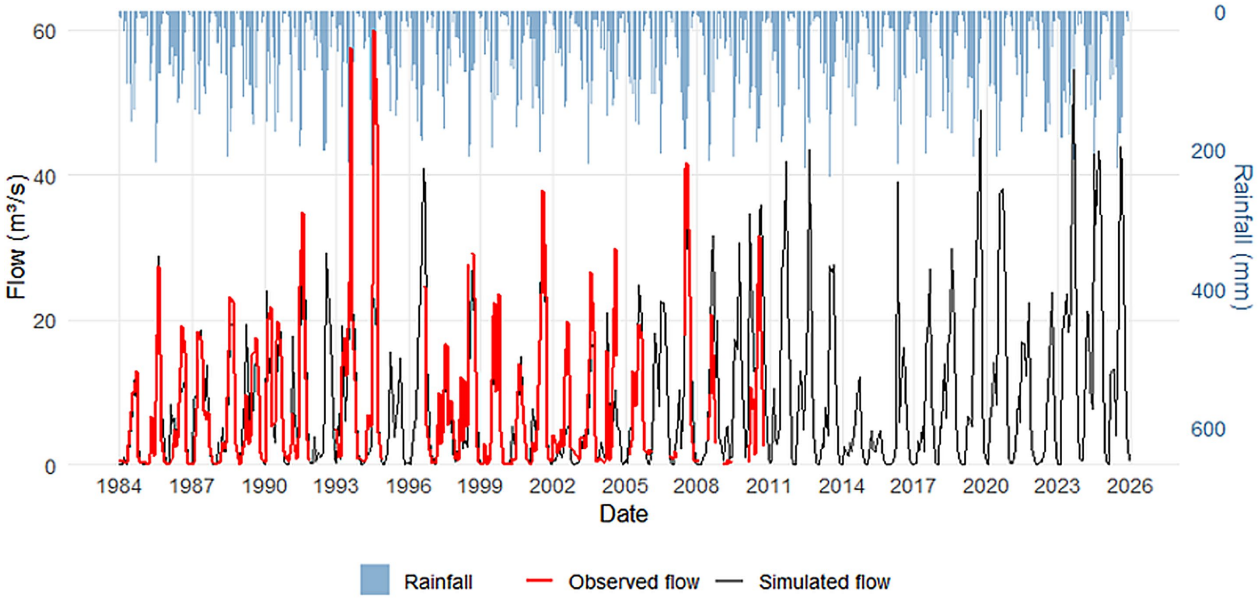



*Figure 8: Observed and SWAT-simulated monthly streamflow at the Meki gauging station, with catchment rainfall (inverted axis), 1984–2025*

Of the 913 mm mean annual rainfall in the Meki catchment, 751 mm (82%) returns to the atmosphere as evapotranspiration, and only 136 mm (15%), about 304 million m³ per year, becomes water yield (Figure 9). About 56.4 mm per year recharges the shallow aquifer. Most of this returns to the rivers as baseflow (28.8 mm) or evaporates from the shallow water table (24.8 mm), and only 2.8mm reaches the deep aquifer. Shallow groundwater and river flow are therefore connected: wells close to rivers reduce the dry season flow available to downstream users and to Lake Ziway. When looked over the course of a year, water is not scarce: the dry-season irrigation demand equals only about 14% of the annual water yield. Constraint is the timing of water availability. Only 10% of the annual flow (about 31 million m³) occurs from December to March, and January and February are the driest months (Figure 10). Baseflow sustains about half of the river flow in December but less than 10% in February and March, when flow depends on the unreliable Belg rains.

Dry-season water yield is highest in the western and north-western highlands and lowest on the rift floor and in the eastern sub-catchment (Figure 11). The rift floor, where most groundwater and mixed-source irrigation is located, receives its river water from the highlands, so upstream diversions directly reduce the water available downstream.

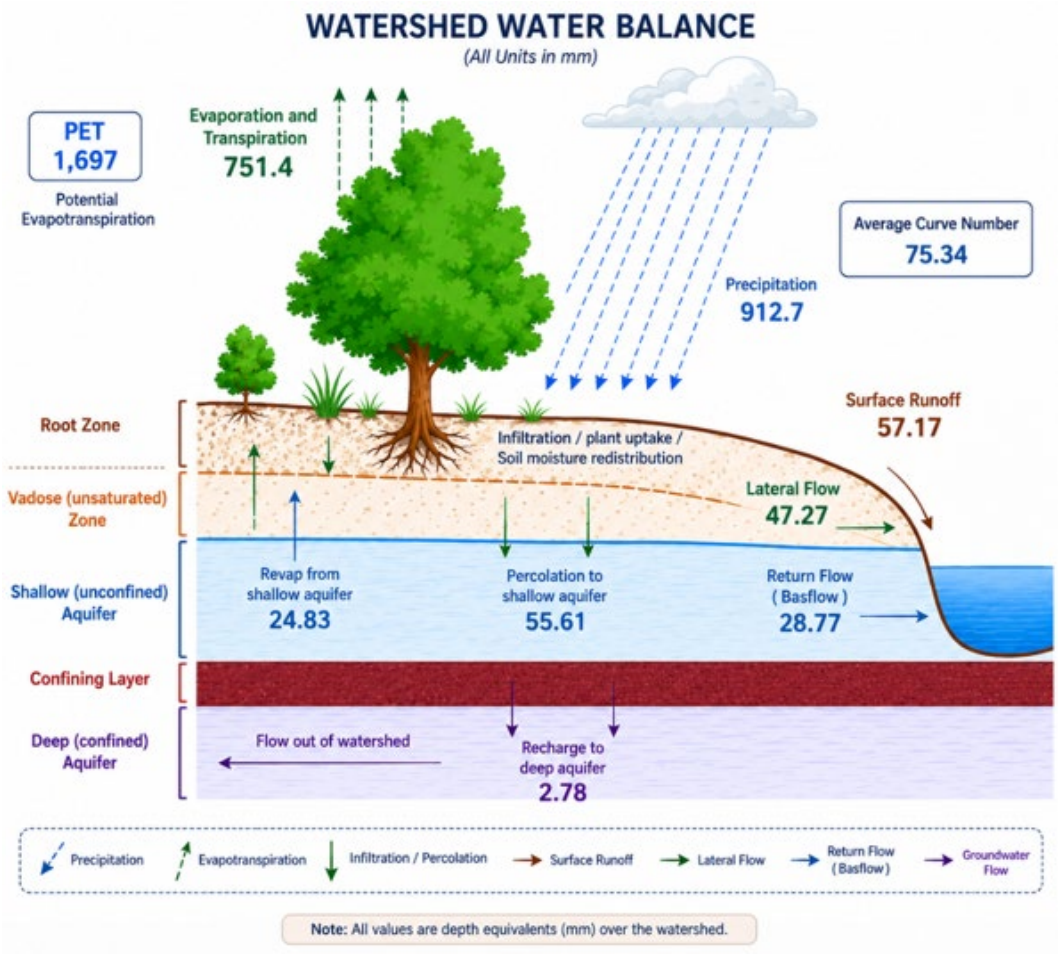



*Figure 9: Long-term average annual water balance of the Meki catchment simulated with SWAT from 1984 to 2025 (depths in mm over the catchment).*

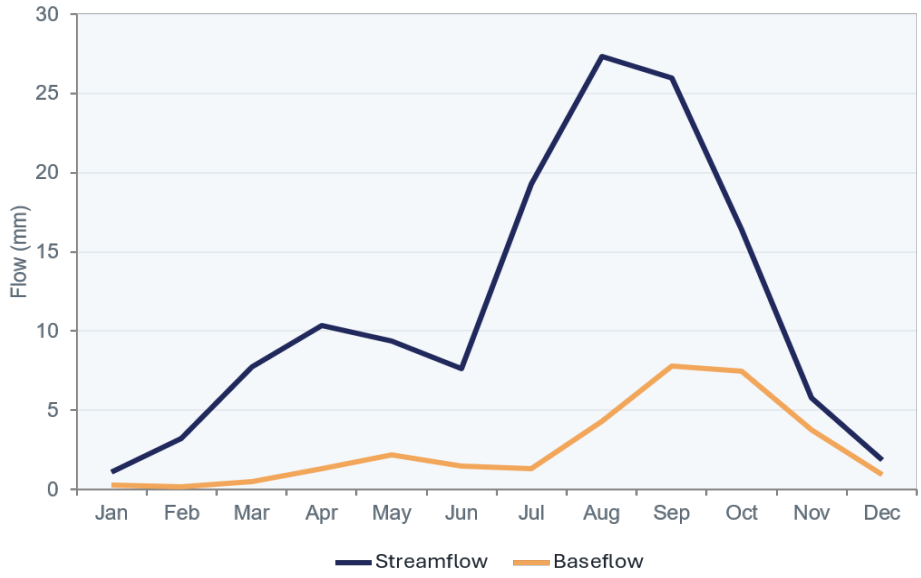



*Figure 10: Long-term average monthly pattern of streamflow and baseflow for the Meki catchment*

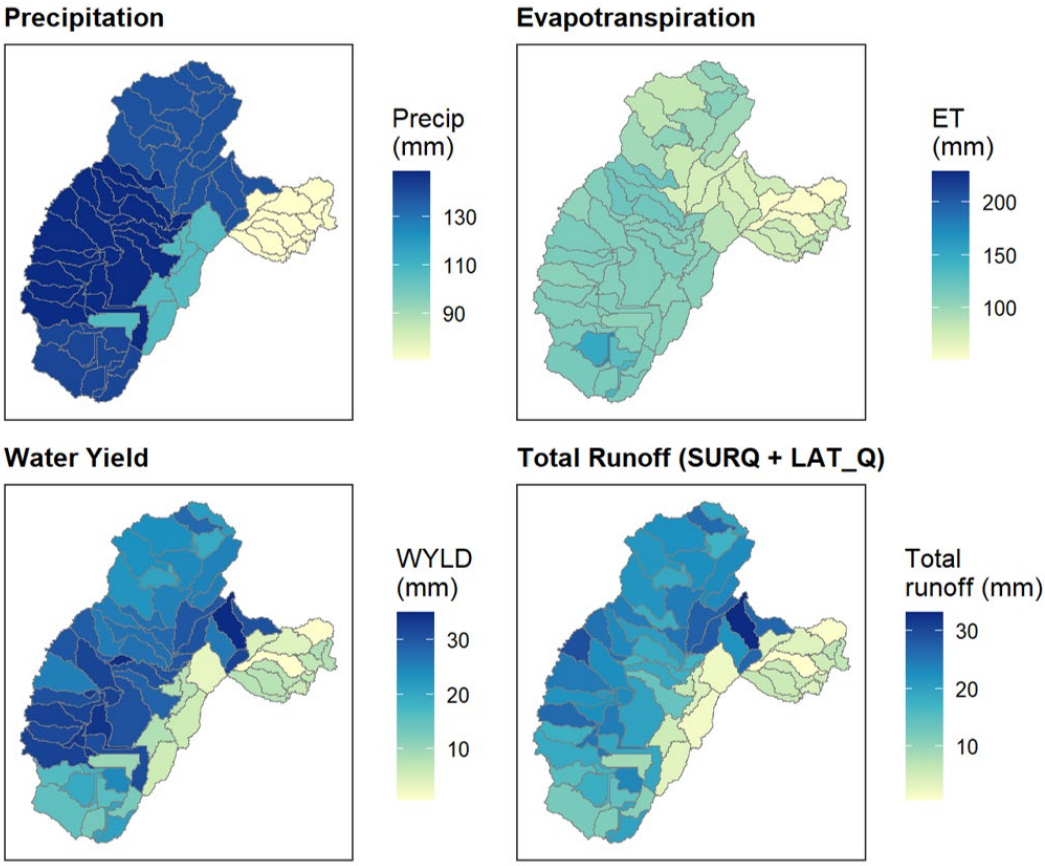



*Figure 11: Long-term average spatial distribution of dry-season (December–March) precipitation, actual evapotranspiration, water yield (WYLD) and total runoff (surface runoff (SURQ + lateral flow (LAT_Q) per sub-catchment simulated with SWAT (mm)*

To identify surface water deficit, the surface water of each sub-catchment was allocated to irrigation demand, first to surface-water-only areas and then to mixed-source areas; groundwater-only areas received no surface water (Figures 12 and 13). This reveals two different situations. The upstream surface water schemes face water shortage in every irrigation month up to more than 530 thousand m³ per month, and groundwater in those locations is limited. This shows the need for demand management and storage facilities rather than groundwater wells. Along the river network, water shortages for irrigation of up to 150 thousand m³ per month occur only in January and February. Areas with these large water shortages are suited for conjunctive water use, with more surface water use from the river in December and March, while January and February can be supplemented by groundwater. The SWAT model assessment can be used as a diagnostic tool for estimating surface water deficits; however, it does not explicitly account for surface water–groundwater interactions. The estimated water shortages should be considered as minimum value, because water was not reserved for environmental flows or inflow to Lake Ziway. When these water demands are considered, the shortage of water will be higher.

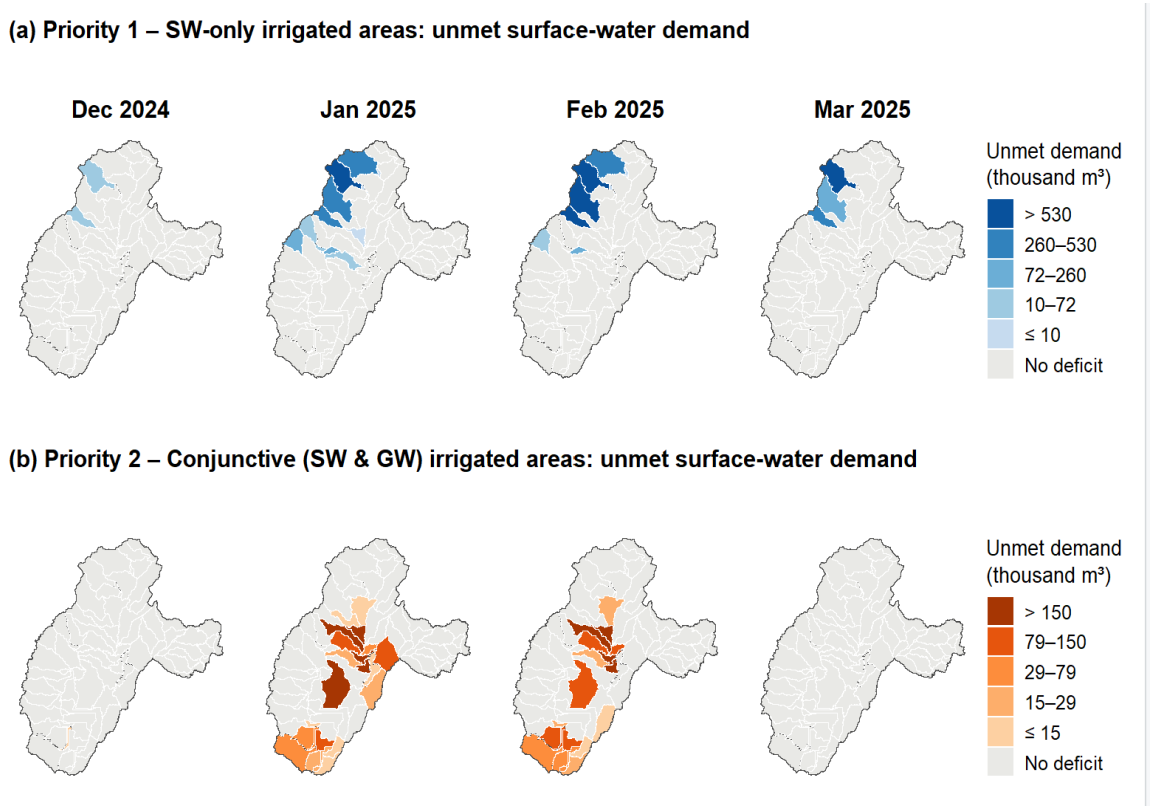



*Figure 12: Unmet irrigation demand (thousand m³) under surface-water-priority allocation, during the 2024-2025 dry season (December 2024 – March 2025): (a) in surface-water-only irrigated areas; (b) in mixed surface water–groundwater irrigated areas. Note: SW – surface water; GW - groundwater*

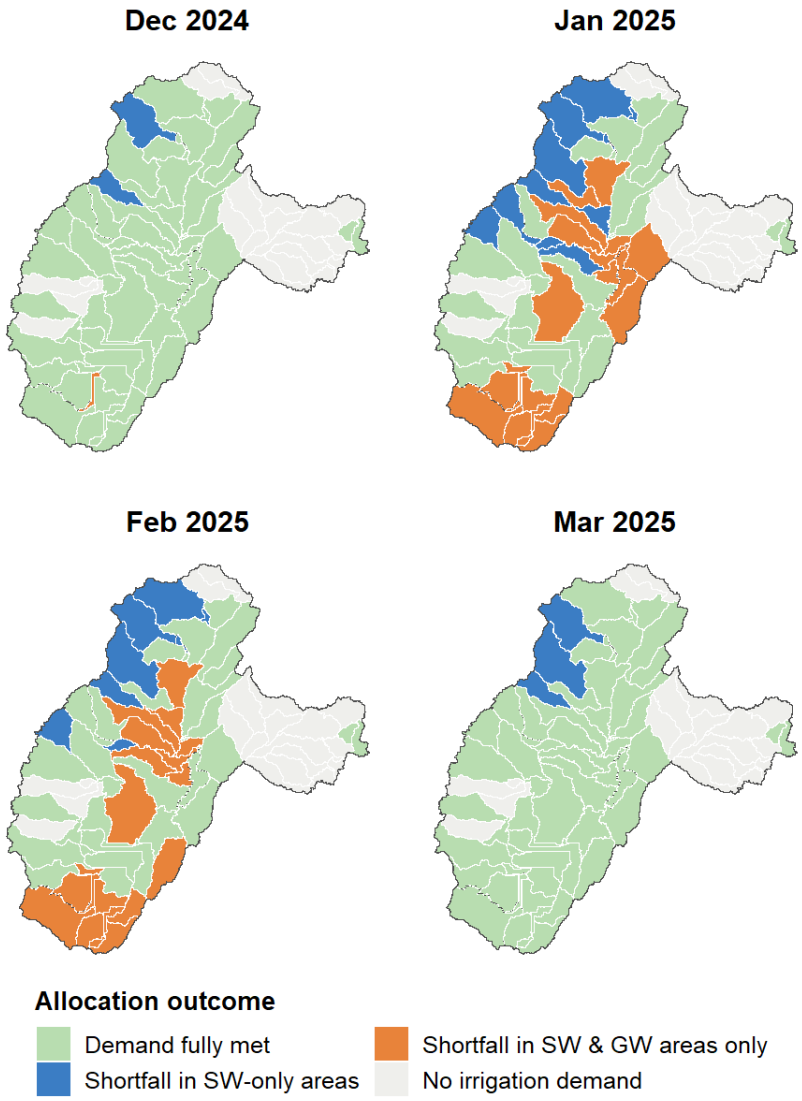



*Figure 13: Outcome of allocating surface water to meet the irrigation demand per sub-catchment within the Meki catchment, December 2024 – March 2025.*

**Box 11: Key results – surface water availability and deficits**

- **Water balance:** mean annual rainfall is 913 mm, 82% of rainfall is evapotranspiration and 15% of rainfall becomes water yield (136 mm, about 304 million m³ per year).
- **Timing rather than total volume, is the constraint:** dry-season demand equals about 14% of annual water yield, but only 10% of annual streamflow (about 31 million m³) occurs from December to March.
- **Upstream surface water schemes:** experience water deficits in every irrigation month, exceeding 530 thousand m³ per month. In places with limited groundwater availability, demand management and water storage options are needed.
- **River corridors on the rift floor:** experience water deficits up to 150 thousand m³ per month in January and February. These locations are suited for conjunctive use.
- **Caveat:** the estimated water deficits are minimum estimates because environmental flow requirements and Lake Ziway inflow requirements were not included in this simulation.

## Groundwater availability estimation

This section describes how groundwater availability was simulated using MODFLOW, including model setup, calibration, and results. The groundwater flow system was modelled using MODFLOW-NWT (Niswonger et al., 2011) using the ModelMuse modelling environment/user interface (Winston, 2009). MODFLOWNWT is a standalone program that is intended for solving problems involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation (Niswonger et al., 2011).

### Conceptual model

The conceptual setup of the MODFLOW model is based on limited available data and some previous studies (Ayenew, 2001, Ministry of Water Resources, 2009). The active model domain covers the whole Meki catchment and has an area of 2,236 $km^2$. The inflow into the model domain consists of recharge from precipitation and the Meki River. The outflow includes pumping for irrigation and domestic use, evapotranspiration, discharge to Meki River and lateral groundwater outflow through the catchment outlet.

### Model discretization

The model domain is discretized into 702 rows and 660 columns with a uniform horizontal grid size of 100 m x 100 m. Vertically, the aquifer is divided into two layers: an upper layer, approximately 30 m thick, comprising the alluvial and weathered zone; and a lower layer, approximately 100 m thick, dominated by the fractured zone, but which may also include alluvial and fractured material. The top layer coincides with the land surface elevation, which was determined from SRTM 30m x 30m DEM. The top layer was simulated as an unconfined aquifer while the second layer is convertible. A convertible layer designation allows the code to switch from confined to unconfined conditions, or vice versa, without user intervention depending on the relative position of simulated water level with respect to model top elevation. When the simulated head in unconfined aquifer is above the top of the model layer it is treated as confined aquifer and when the simulated head drops below model top in the case of confined aquifer it will be simulated as an unconfined aquifer. Temporally, the model was divided into 12 stress periods representing the long-term average of 2000-2025.

### Boundary conditions

No flow boundaries were assigned along lateral boundaries that coincide with watershed boundaries except at the catchment outlet where we defined General Head boundary (GHB). A GHB in MODFLOW is a boundary condition specifying a given head at the boundary of the model area. This can be specified as a time series of varying heads. It is used to represent a boundary condition where water enters or leaves the model area at a rate proportional to the head difference between the specified head and the head in the model cell.

### Initial condition

The governing equation of groundwater in MODFLOW is solved by using finite difference. Hence, it requires water level at the beginning of the time steps to calculate the head distribution at the end of the time steps. For each time step, the water level at the start of one-time step is set equal to the water level at the end of the previous time step. This chain of water level calculations starts from user-specified initial head values, which are commonly known as initial conditions. Initial conditions do not have influence on steady state simulation; however, this affects transient model simulation with a fading effect as time progresses. The classical approach for defining initial head for transient model simulations follows a two-step procedure, whereby firstly a steady state model is calibrated for a pre-development period, and secondly using the output of the steady state model as initial head for transient simulation.

The MODFLOW model was designed to simulate dynamic equilibrium over a 1-year cycle of average monthly hydrologic conditions stresses, which are defined as the mean monthly conditions that occurred over a multiyear period of record. The cycle of average monthly

stresses is repeated from one year to the next. As used here, dynamic equilibrium is the condition in which there is no net change in groundwater storage over the annual hydrologic cycle. It was found that simulation of three to five annual cycles was sufficient to establish dynamic equilibrium.

### Aquifer properties

The magnitude and spatial distribution of aquifer properties such as hydraulic conductivity and storage coefficient (specific storage and specific yield) are required for the model. Hydraulic conductivity is one of the highly spatially variable parameters. In most cases our knowledge regarding the values of hydraulic conductivity parameter is limited to randomly located point measurements or no measurement at all. To define the aquifer parameters, the catchment area was divided into four hydrogeological zones based on the recently developed 1:250,000 hydrogeological map of the catchment (Figure 14). This map is digitized from the Hydrogeological Maps of Akaki Beseka (NC 37-14, 2013) and Hosaina (NB 37-2, 2019), at 1:250,000 scale. (Geological Survey of Ethiopia & Czech Republic Development Cooperation, 2013, 2019). Initial estimates of hydraulic conductivity, parameters were obtained from the literature values and pumping test data points.

### Recharge

Recharge is obtained from the SWAT model. This recharge represents the recharge from precipitation (diffuse recharge). Recharge is calculated from HRU output and is applied to the upper most active layer of the model using recharge package. As recharge is highly variable in space and time and these variations are difficult to estimate using SWAT recharge estimate provides a more reliable estimate.

### Groundwater Evapotranspiration

Groundwater evapotranspiration (GWET) occurs in areas where the depth to groundwater is shallow (e.g. riparian areas), and plant roots penetrate to the zone of saturation. To simulate GWET using the Evapotranspiration Package in MODFLOW, maximum evaporation rate, evapotranspiration surface and extinction depth need to be specified in the model. A maximum evapotranspiration rate is assumed to occur when the water table is at the land surface. The extinction depth was determined based on Shah et al. (2007) for a given soil type and land cover and assumed to be 3 m. The maximum evaporation rate was defined as the difference between potential and actual evapotranspiration calculated by SWAT.

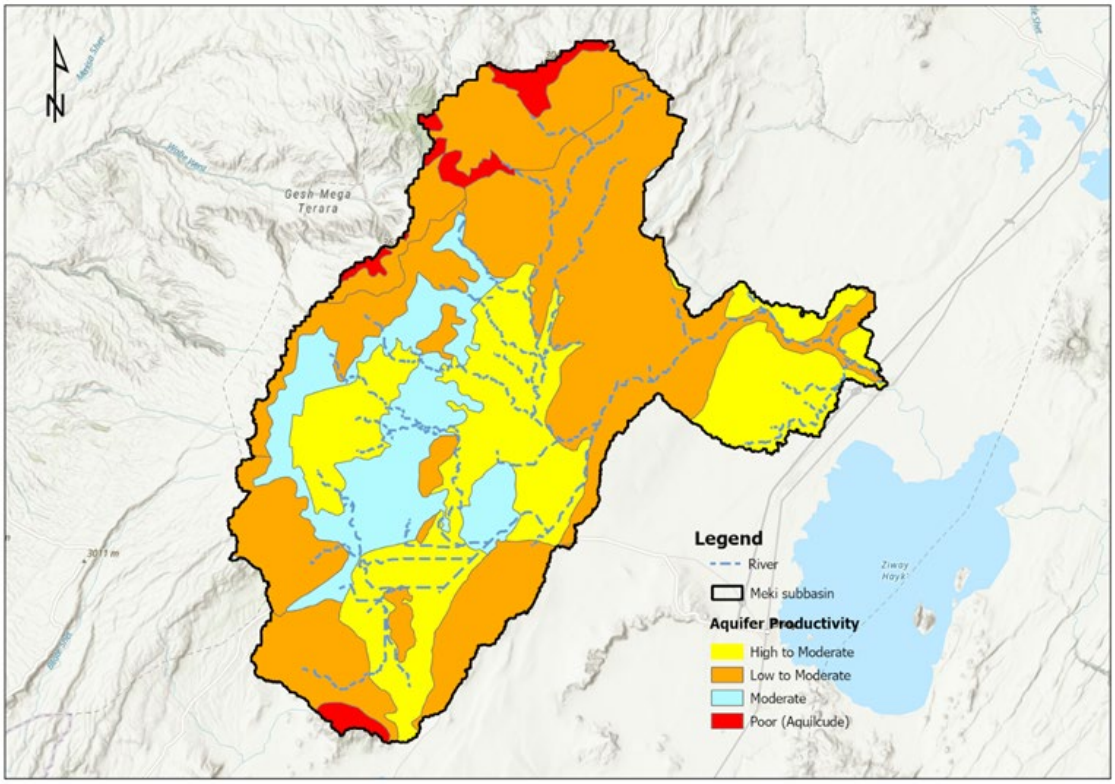



*Figure 14: Hydrogeological zones of the Meki catchment. ARCPro GIS software is used to generate this map.*

### River-aquifer interaction

The river channels were represented with 81 river segments corresponding to 81 SWAT subbasin reaches. The river channel cross-sections were assumed to be rectangular. Water added by precipitation directly on the stream channels and water removed by evapotranspiration directly from the stream channels were assumed to be negligible and disregarded. Surface runoff entering stream segments were obtained from SWAT. Due to lack of data, vertical streambed hydraulic conductivity, manning roughness coefficients and streambed sediment thickness were assumed to be uniform across the 81 stream segments. The thickness of the streambed material was assumed to be 1 m for all segments. Streambed elevation and river channel cross-section were extracted from the digital elevation model. Initial values for the Manning roughness coefficients were obtained from the literature (Arcement and Schneider, 1989) and the final values were determined through model calibration together with the streambed hydraulic conductivity. The elevation of the top of the stream bed is specified for the beginning of the first reach and the end of the last reach. The program linearly interpolates between the two values. The streambed elevation at the upstream and downstream end of the stream segments were defined based on DEM minus assumed channel incision values.

### Spring discharge

There are 32 springs in the Meki catchment (AG Consult, 2007). As these springs discharge groundwater from the aquifer, they were simulated using the Drain Package. In this package, the discharge rate is proportional to the head difference between the aquifer and the drain, multiplied by the conductance of the interface between the aquifer and the drain. When the groundwater level in the aquifer exceeds the drain elevation, an outflow occurs; otherwise, no outflow is simulated.

### Groundwater pumping

Groundwater pumping consists of groundwater withdrawal for irrigation, domestic and livestock uses. The location and abstraction rates for pumping wells both shallow and deep wells were obtained from a database compiled during the Butajira-Ziway Area Development Study Project (AG Consult, 2007). A total of 132 pumping wells were used to represent groundwater pumping for domestic uses. Abstraction for irrigated fields was estimated indirectly from crop consumptive use (evapotranspiration). The total irrigation water requirement was estimated for the dominant crop, tomato. A total of 1,719 irrigation pumping wells were simulated, comprising 945 wells supplying groundwater-only irrigation and 774 wells providing supplemental pumping in conjunctive use areas.

### Modeling the effect of faults and dykes on groundwater flows

Faults and dykes may act as a barrier to groundwater flow. To simulate the effect of faults and dykes on groundwater flow we used the Horizontal Flow Barrier Package (HFB) (Hsieh and Freckleton, 1993). The HFB reduces horizontal hydraulic conductance between model cells. The input data required for HFB are the barrier hydraulic conductivity and the barrier thickness. This ratio of hydraulic conductivity to barrier thickness is known as hydraulic characteristic. Since information on the hydraulic conductivity and thickness of the faults are not available a constant value of hydraulic characteristic value was used for all barriers, and this value was adjusted during model calibration.

### Steady state model calibration

The steady-state model was calibrated using static water level data in 112 wells from the database (AG Consult, 2007). During model calibration hydraulic conductivity in the four zones and vertical hydraulic conductivity of the riverbed, manning roughness and GHB conductance were varied until the simulated head matched the observed values. Automatic calibration was performed using Parameter ESTimation (PEST). PEST is a model-independent non-linear parameter estimator. PEST automatically minimizes the sum of square errors using the Gauss-Marquardt-Levenberg optimization algorithm in a weighted least-square sense. During the optimization, observations were assumed to be equal weight (equal importance in determining the optimization outcome).

### Transient model calibration

The transient model was calibrated using the hydraulic conductivity values obtained from the steady-state calibration, with the simulated steady-state heads used as the initial heads. Because groundwater level time-series data is not available, baseflow simulated by the SWAT model was used as a proxy for transient model calibration. The storage parameters (specific yield and specific storage) were adjusted manually in each of the four hydrogeological zones until the baseflow simulated by MODFLOW, using the Streamflow-Routing (SFR) package, matching the SWAT-simulated baseflow. The calibrated model parameters for hydraulic conductivity, specific yield, specific storage and boundary condition parameters are given in Annex Tables 2 and 3).

## MODFLOW Model Results

### Steady state model calibration results

Model performance was evaluated using both statistical and qualitative criteria. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) between observed and simulated groundwater levels were 14.8 m and 9.6 m, respectively, indicating a good fit between the two datasets. The scatter plot of observed versus simulated groundwater levels (Figure 15) shows a strong correlation. Since RMSE alone does not indicate whether a model's fit is good without considering the range of the observed dataset, a Normalized RMSE (NRMSE) was calculated by dividing the RMSE by the range of observations. NRMSE values range from 0 to 1, with

values closer to 0 indicating a better fit; an NRMSE below 0.1 is generally considered acceptable for regional groundwater models.

Beyond these statistical measures, the spatial behavior of the model was also assessed. Residuals were randomly distributed across monitoring sites, and the simulated groundwater level contours agreed with regional groundwater flow directions. According to Hill (1998), a well-calibrated model should exhibit randomly distributed residual errors and yield optimal parameters that are physically realistic. Finally, the water balance between inflow and outflow was verified to remain within the recommended 1% threshold. A mass balance discrepancy exceeding 1% would indicate a potential numerical problem and could invalidate the simulation results (ASTM Standard D5447, 2010).

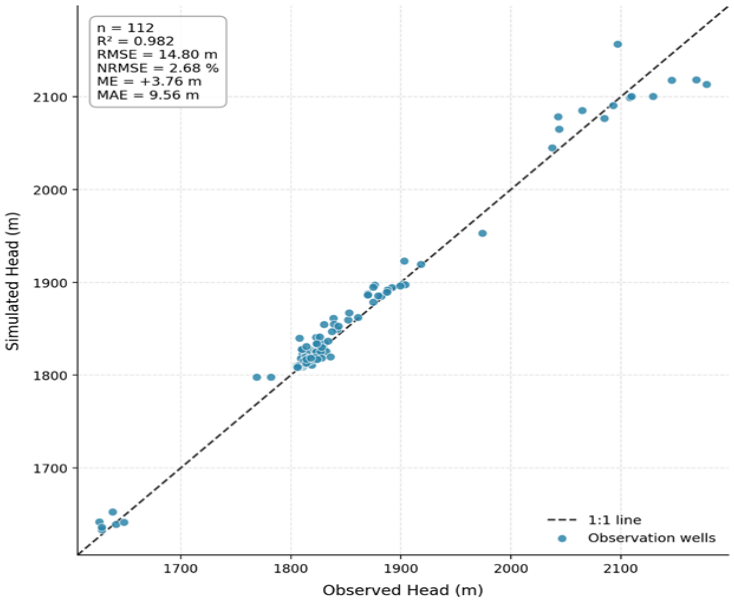



*Figure 15: Observed versus simulated groundwater levels for the steady-state MODFLOW model calibration.*

**Transient model calibration results**

The comparison between SWAT baseflow and SFR-simulated baseflow shows a strong correlation, with a coefficient of determination ($R^2$) of 0.85 and a NSE of 0.69, indicating good model performance. The RMSE and MAE were 117,281 $m^3/d$ and 78,863 $m^3/d$, respectively, while the RMSE-observations standard deviation ratio (RSR) of 0.56 falls within the satisfactory range. The Percent Bias (PBIAS) was 22.35%, indicating that the SFR model systematically underestimates baseflow relative to SWAT. This underestimation is particularly pronounced during the September–November period, where large differences occur between the two datasets. These performance statistics suggest that the MODFLOW-SFR model reasonably reproduces the temporal pattern of baseflow simulated by SWAT, although the tendency toward underestimation, especially during the September–November period (Figure 16).

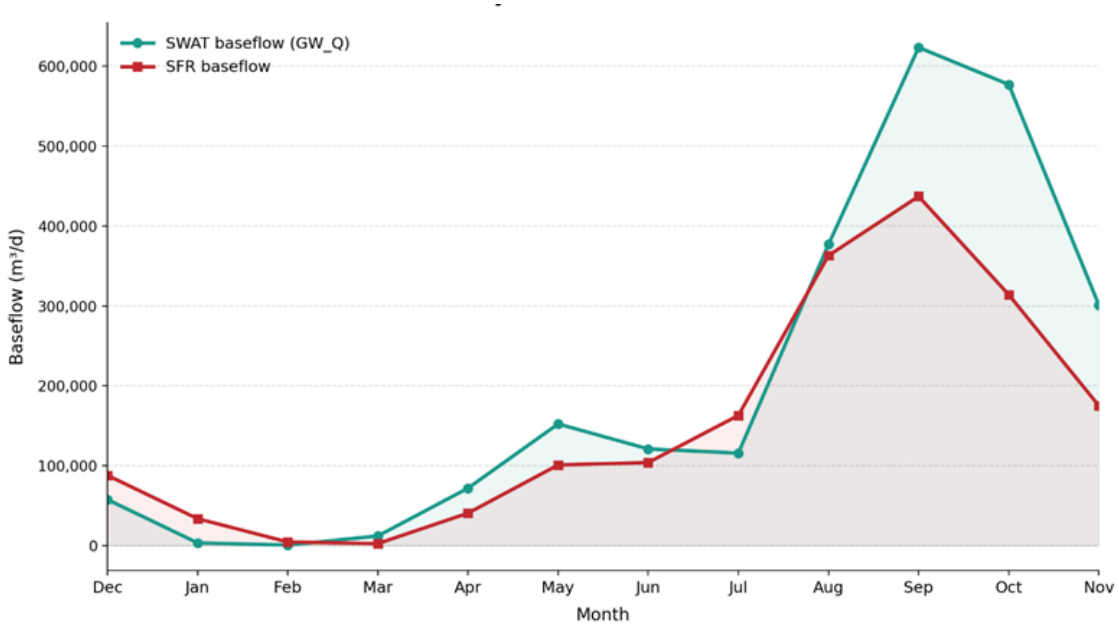



*Figure 16: Comparison of monthly baseflow simulated by SWAT and by the MODFLOW SFR package at the Meki catchment outlet*

**Box 12: Key results – groundwater model performance**

1. **Steady-state calibration**: RMSE of 14.8 m, MAE of 9.6 m, NRMSE of 2.7% and $R^2$ of 0.98 against static water levels in 112 wells; residuals are randomly distributed and the water balance error is below 1%.
2. **Transient calibration**: $R^2$ of 0.85, NSE of 0.69 and RSR of 0.56 against SWAT-simulated baseflow; PBIAS of 22% indicates underestimation, mainly from September to November.
3. **Main limitation:** lack of groundwater levels time series and observed baseflow forced to be dependent on SWAT-simulated baseflow for comparison.

## Step 4: Conjunctive use modeling

Conjunctive-use modeling was performed using MODFLOW-NWT's Agricultural Water Use (AG) Package, which simulates the conjunctive use of surface water and groundwater by automatically pumping groundwater whenever surface water availability falls short of demand. Since the AG Package is not supported by the ModelMuse interface, the transient calibrated MODFLOW-NWT model developed in ModelMuse were instead used to run the MODFLOW-NWT-AG Package outside of the interface. Irrigation demand was calculated based on the dominant crop type and specified as input to the diversion flow requirement in the SFR package. Non-irrigation wells, such as public supply wells, are handled outside of the AG Package. Irrigation supplied by diversion segments and groundwater wells is applied to designated cells based on a user-specified mapping between numerically identified SFR segments and the corresponding irrigated fields. Additional constraints can be applied to surface water diversions using diversion rates and one of four diversion priority options available in the SFR package. In this conjunctive-use assessment, priority option zero (IPRIOR = 0) was used, under which any diversion demand exceeding the available flow is met only up to the amount available, leaving no flow for downstream or tributary segments and making no provision for environmental flows.

The AG Package of MODFLOW-NWT was configured following a structured workflow to simulate conjunctive use of surface water and groundwater for irrigation. First, diversion segments were assigned at the last reach of each relevant segment in the SFR package, marking the points where surface water could be diverted for irrigation. SFR diversion flow rates are constrained by the amount of water flowing in the upstream segment, together with one of four available water-use priority options, which govern how diversion demand is satisfied when supply is limited. Crop water demand was calculated for each irrigated area as in Step 2 and assigned as the flow entering the upstream end of the corresponding diversion river segment. To avoid double-counting, since MODFLOW-SFR separately calculates baseflow based on aquifer–river exchange, the sum of runoff and lateral flow from SWAT was input as the "Runoff" term in the corresponding SFR segment.

Within the AG Package, each diversion segment was mapped to its corresponding irrigated MODFLOW cell(s), and each supplementary pumping well was similarly mapped to the cell(s) it irrigates. Finally, the maximum pumping capacity of each supplementary well was defined, setting the upper limit on groundwater withdrawals available to meet irrigation demand when surface water supply was insufficient.

**Conjunctive Use Model Results**

The results of the conjunctive-use modeling are presented in two complementary ways. First, the spatial distribution of water demand, supply, and deficit is presented by sub-catchments, illustrating how these components vary across the study area and highlighting sub-catchments where surface water alone is insufficient to meet irrigation demand. Second, the temporal distribution of surface water supply and groundwater contribution is presented for each sub-catchment, showing how the relative contribution of surface water versus groundwater changes over time, particularly during periods of reduced surface water availability, when groundwater pumping is triggered to meet the deficit.

Figure 17 shows the spatial distribution of demand, surface water supply, surface water deficit, and groundwater supplement across the sub-catchments. The results show that demand and deficit peak in February, easing slightly by March, while December shows minimal stress across the basin. Groundwater demand is highest in the north-central sub-catchments, where the main irrigation structures are located; however, these same high-demand sites also have low surface water availability. As a result, the deficit remains high in these modernized irrigation areas, and this deficit cannot be met by groundwater, as groundwater is not available in sufficient quantity at these locations.

Figure 18 shows the 81 SWAT sub-catchment and the two sub-catchments selected for demonstration of the temporal dynamics of conjunctive use of surface and groundwater. Figure 19 the monthly surface water and groundwater contribution during the irrigation season for a sample sub-catchment, sub-catchment 24. As shown, in December, demand was fully met by surface water, with no groundwater use required. In January, surface water availability declined while demand rose sharply, resulting in groundwater supplementing approximately 80% of total supply. By February, surface water had dropped to zero, and groundwater alone met the full irrigation demand. In March, surface water availability recovered and was sufficient to meet the rising demand, eliminating the need for groundwater use. In contrast, Sub-catchment 61 demonstrated a markedly different pattern (Figure 20). Groundwater was the dominant water source in this sub-catchment, meeting over 99% of irrigation demand in all four months, while surface water contributed only a minor share (approximately 1,100–2,800 $m^3$/month) that is small relative to total demand. Combined supply closely tracks demand throughout the irrigation season, with minimal shortfall. Overall, sub-catchment 61 operates primarily as a groundwater-dependent irrigation system.

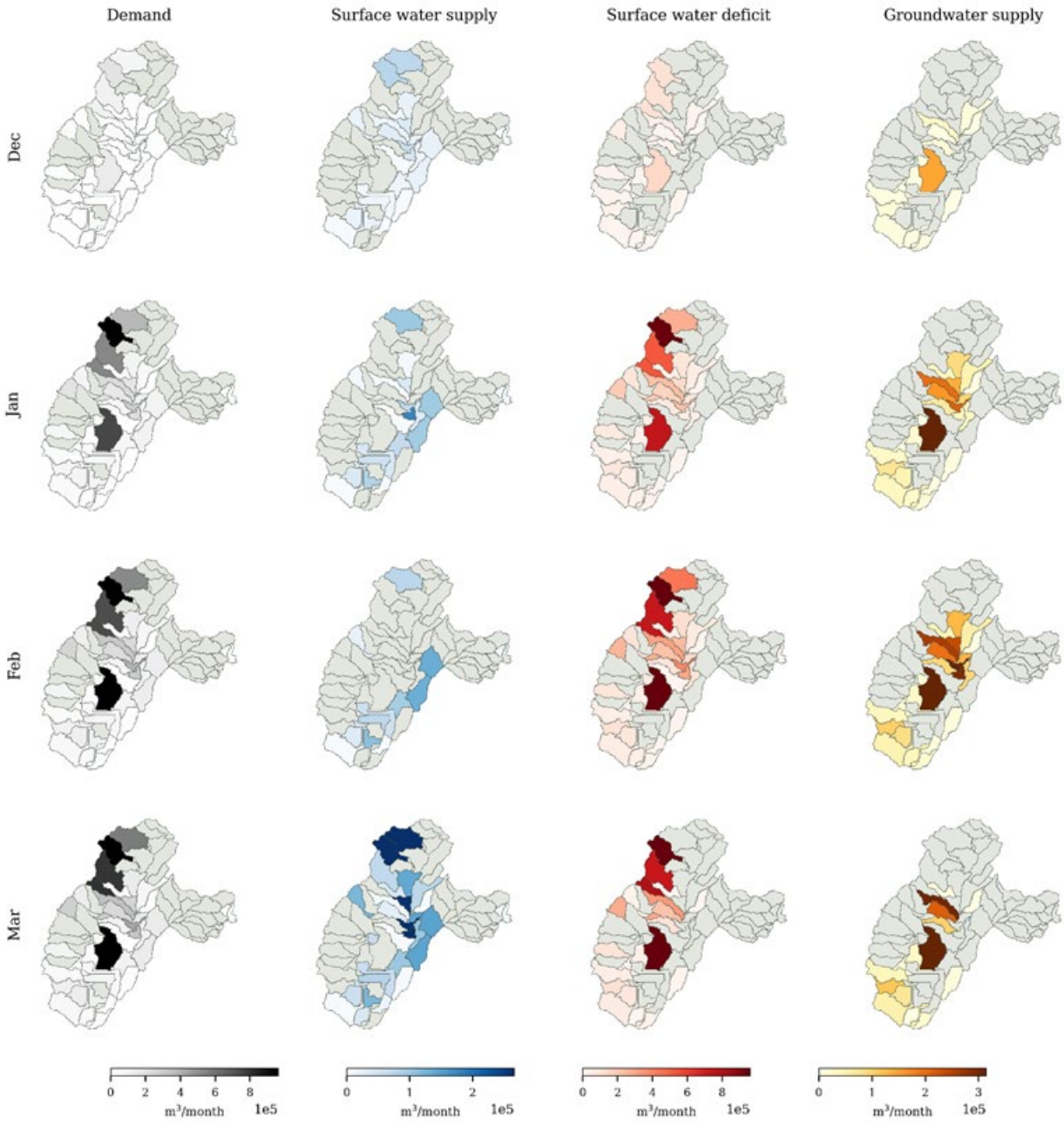



*Figure 17: Long-term simulated spatial distribution of monthly irrigation water demand, surface water supply, surface water deficit, and groundwater supply across the Meki catchment during the irrigation season (December-March).*

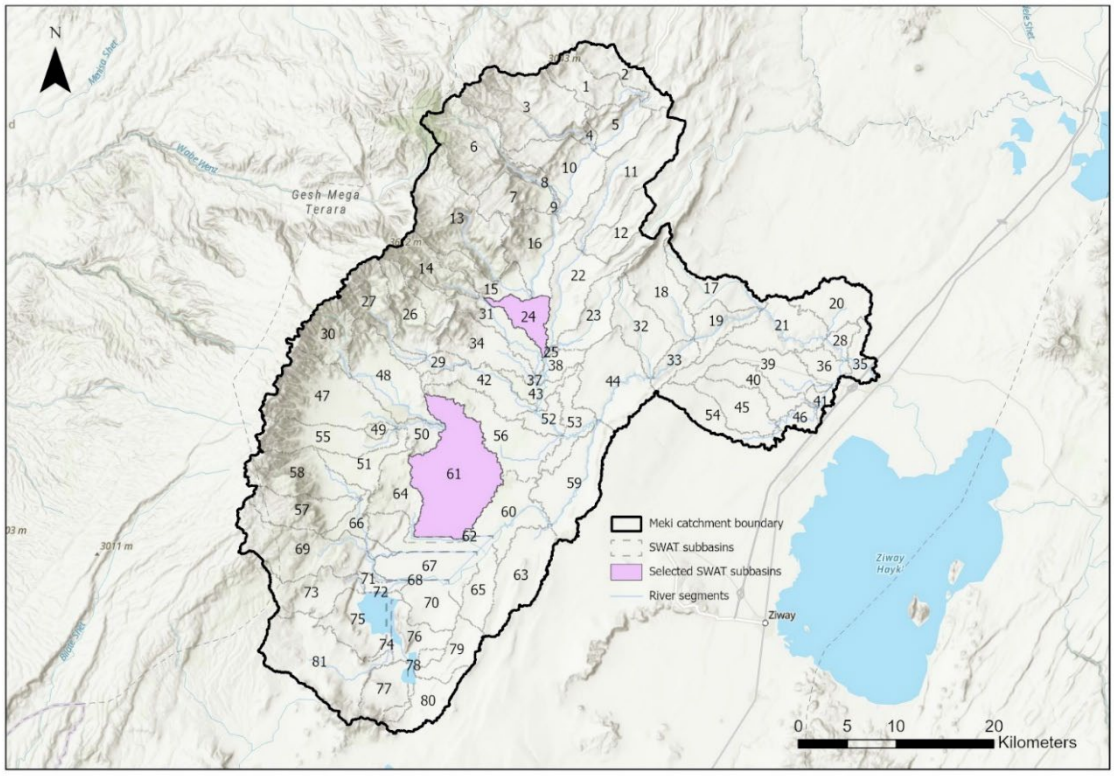



*Figure 18: The 81 sub-catchments as delineated by SWAT and selected two sub-catchments for conjunctive use demonstration*

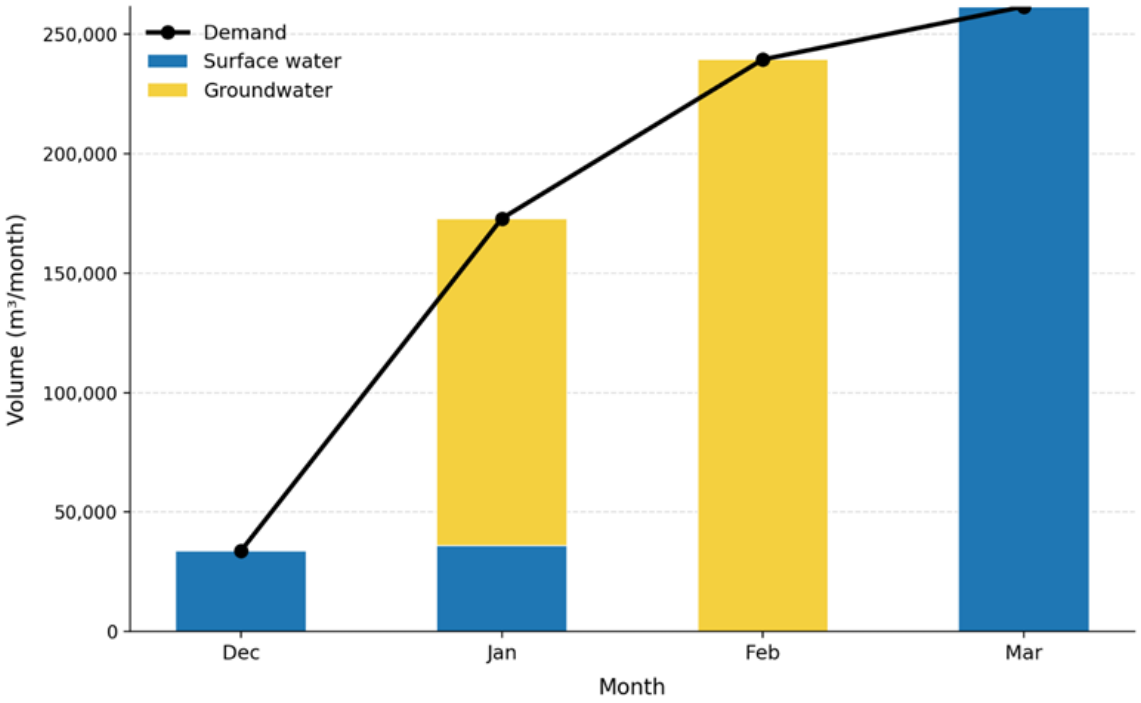



*Figure 19: Simulated monthly irrigation water supply in sub-catchment 24 during the growing season, showing surface water supply and the deficit met by groundwater.*

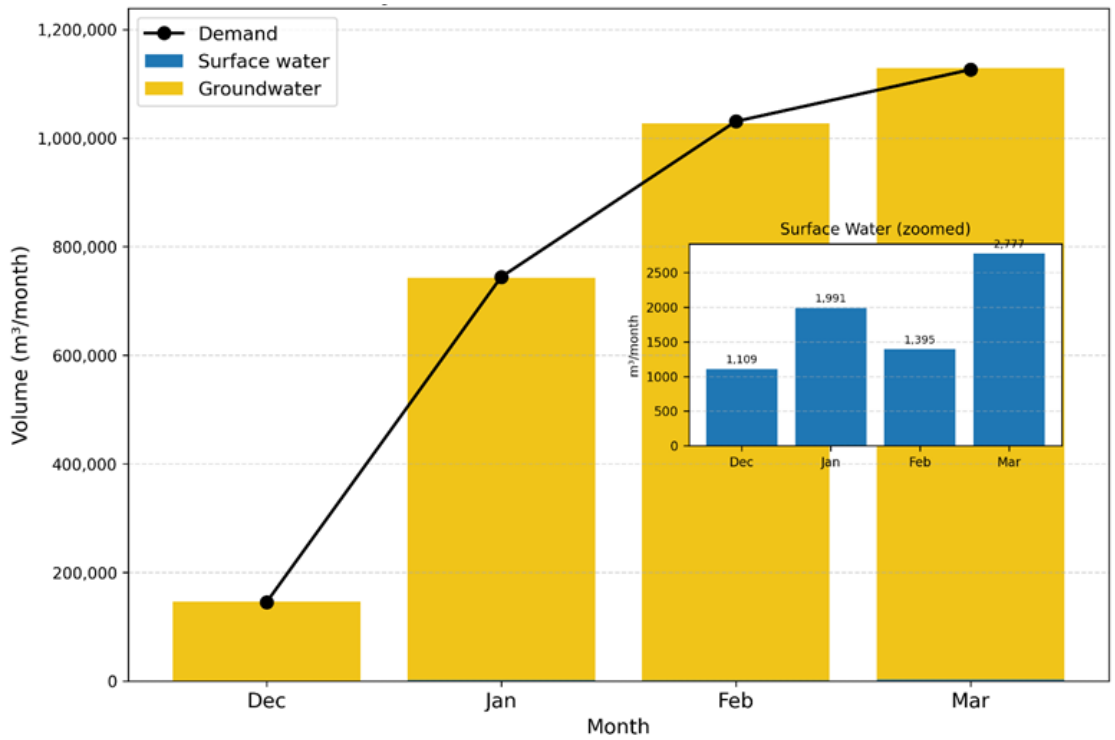



*Figure 20: Simulated monthly irrigation water supply in sub-catchment 61 during the growing season, showing surface water supply and the deficit met by groundwater.*

## Step 5: Sustainability limits for water abstraction

For the Meki catchment, following Mekonnen et al. (2026), the environmental flow was set at 20% of the mean monthly flow, and the sustainable limit of surface water abstraction was therefore taken as 80% of the mean monthly flow. In the Meki catchment, the environmental flow was not deducted from the available surface water, because farmers currently withdraw irrigation water without reserving water for the environment. During the dry season, irrigation water demand was found to exceed the total river flow, well beyond the sustainable limit of 80% of the mean monthly flow. As a result, the river dries during this period, leaving no flow to maintain its ecological functions. This shows that surface water is currently abstracted beyond its sustainable limit in the dry season, which indicates unsustainable surface water use and no room for further dry-season irrigation development from the river's dry season water volume.

In the case of Meki catchment, the groundwater situation is different from the rivers. The ratio of groundwater abstraction to average annual recharge is found to be about 6%. With this value on an annual basis, the study area falls within the Scenario 1 range which is annual abstraction below 90% of annual recharge. This shows that currently, a very small share of the annual groundwater recharge is being abstracted for different uses, which indicates sustainable groundwater use and considerable room for further development from shallow groundwater sources in the catchment. However, the need for monitoring of groundwater is stressed as more irrigation expansion occurs using this water resource.

**Box 13: Implication of key results from conjunctive use modeling in the Meki catchment**

1. **Dry-season water scarcity is primarily about timing and location, not annual volume.** Estimated irrigation water demand peaks in February-March, when river flows are lowest, creating water shortages despite adequate annual water yield.

2. **The simulation indicates potential for groundwater to strategically supplement surface water where both sources are available.** Rift-floor part of the catchment is suitable for planning conjunctive use, particularly in February-March. However, pumping must be monitored because groundwater and river flows are connected.

3. **Upstream shortages may be better addressed through demand management and surface water storage rather than more groundwater pumping.** Catchment-wide allocation rules and upstream–downstream coordination are also needed.

4. **Actual surface water deficits and groundwater needs can be larger than shown.** Since environmental flows and downstream water need for Lake Ziway was not considered in this baseline assessment, actual water deficits may be larger. Environmental flow thresholds should be set before surface water is allocated.

## Limitation of conjunctive water use modeling

1. Irrigated areas were mapped from remote sensing, which may not detect small plots because of limited spatial resolution. The analysis used the maximum irrigated area across the season, whereas the area actually irrigated varies from month to month as crops are planted and harvested. Using the maximum area may therefore overestimate demand in some months.
2. Irrigation water demand was estimated using tomato, the dominant crop, and an assumed irrigation efficiency. Because farmers grow a mix of crops with different water requirements, and efficiency varies in practice, actual irrigation demand may differ from the estimate.
3. Groundwater-only and conjunctive-use irrigation were distinguished using a 500 m buffer from the river, based on field observations. Because the extent of river water use likely varies between sites, a uniform buffer may misclassify some irrigated areas. Mapping the actual water sources of irrigated plots would improve this classification.
4. Pumping rates of existing domestic and irrigation boreholes were taken from a previous inventory and assumed constant over the simulation period. However, new wells have likely been drilled since then, as observed during the field visit, and pumping varies seasonally. Simulated abstraction may therefore underestimate actual pumping. An updated well inventory would reduce this uncertainty
5. The steady-state MODFLOW model was calibrated using static water levels collected at different times, so calibration results may be influenced by temporal variability in groundwater levels.
6. In the absence of groundwater level time series, the transient MODFLOW model was calibrated against SWAT-simulated baseflow. This introduces uncertainty because (1) catchment-scale baseflow cannot fully constrain spatially varying aquifer properties, allowing multiple parameter-sets to fit equally well, and (2) the calibration inherits the uncertainties of the SWAT model.
7. The groundwater-only irrigation wells and conjunctive-use wells are hypothetical, with locations assigned based on irrigated areas rather than mapped well data. As a result, the simulated spatial distribution of pumping may differ from actual conditions, which could affect the accuracy of local drawdown and groundwater availability estimates.
8. The pumping rates of groundwater-only wells were estimated from irrigated areas and crop irrigation water requirements rather than measured abstraction. This assumes that crop water demand is fully met by pumping, whereas actual rates depend on farmer practices, well capacity, energy costs and deficit irrigation. Simulated abstraction may therefore over- or underestimate actual pumping, affecting the predicted groundwater drawdown.

9. The conjunctive-use simulation did not account for environmental flows, assuming all river flow was available for irrigation. This overestimates water availability as a minimum flow must be maintained for ecosystems and downstream users. Future simulations should include environmental flow requirements.

## Stakeholder consultations

Stakeholder consultations are important avenues to discuss the importance of conjunctive water use in irrigation to support the irrigation expansion goals in Ethiopia. Through the CGIAR Policy Innovation program, IWMI conducted stakeholder consultations with actors ranging from federal ministries on water and energy, agriculture, irrigation and lowlands, regional and woreda level agriculture experts, academia and other partners on the irrigation expansion, water use and coordination among sectors in the Meki catchment. The consultations included understanding the mechanisms to enhance the effectiveness of smallholder irrigation from data, tools, policy and regulation perspective. They also focused on understanding the relationship between federal, regional and woreda level coordination as well as the horizontal coordination among the water, agriculture, and irrigation ministries and the environmental offices.

Stakeholders highlighted challenges from the technical and policy and implementation aspects. Farmers in the Meki catchment reported benefits of irrigation and interest in expanding their production at a fast pace. However, the coordinating mechanisms, regulatory and enforcement provisions, monitoring systems and other relevant aspects are not in place to support the irrigation expansion while protecting water resources. On the technical side, conjunctive use of water is not practiced in a coordinated manner and requires technical guidance on how to implement it. Moreover, at local level, scientific support is needed to determine the different information needed to implement conjunctive water use.

# 4. Recommendations

## Technical considerations

- Manage surface and groundwater as an interconnected system and understand the system's water availability at monthly or seasonal timescale.
- Monitor surface and groundwater levels to properly estimate water abstraction limits.
- Define surface-water and groundwater abstraction limits that protect aquifers, environmental flows, and Lake Ziway inflows.
- Prioritize groundwater supplementation for irrigation during January–February where aquifers can sustainably support it, mostly in the areas where both sources are available. Make sure to monitor groundwater levels to avoid overexploitation.
- In upstream areas of the catchment with limited groundwater, prioritize demand management and assess feasibility of building storage facilities.
- Develop conjunctive-use allocation rules that specify when surface water and groundwater should be used.
- Local experts should be trained to estimate water availability in the catchment, monitor groundwater levels and abstractions, map irrigated areas, and estimate irrigation water demand. Training should involve simulating baseline situations and different scenarios.

## Policy and implementation recommendations

- Strengthen a cross-sectoral coordination mechanism spanning agriculture, water, energy and environmental institutions as there are some efforts by government to implement integrated water resources management.

- Clarify responsibilities for planning, water allocation, monitoring and enforcement across federal, regional, basin, and woreda authorities.
- Create upstream–downstream water-user coordination platforms and conflict-resolution mechanisms.
- Establish groundwater-level and river-flow trigger thresholds for restricting abstraction.
- Strengthen monitoring, compliance and enforcement of abstraction permits, allocation limits, and environmental-flow requirements including Lake Ziway inflow.

## 5. References


Abbaspour, K. C. 2015. SWAT-CUP: SWAT calibration and uncertainty programs—a user manual. *Eawag: Dübendorf, Switzerland*, 16-70.

AG Consult Consulting Hydrogeologists & Engineers Plc (2007). Butajira -Ziway Areas Development Study Project- Hydrogeology, Ministry of Water Resources (MoWR), Ethiopian Water Technology Centre (EWTEC)

Allen, R.G., Pereira, L. S., Raes, D., Smith, M. 1998. *Crop Evapotranspiration - guidelines for Computing Crop Water Requirements* - FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations (FAO), Rome.

Arcement, G., and Schneider, V. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains US Government Printing Office Washington, DC

ASTM Standard D5447, 2010. Standard Guide for Application of a Groundwater Flow Model to a Site-Specific Problem

Ayenew, T. 2001. Numerical groundwater flow modeling of the Central Main Ethiopian Rift lakes basin. *SINET: Ethiopian Journal of Science,* 24, 167-184.

Balasubramanya, S and Lele, U. 2022. Policy Note: Expanding Irrigation in Sub-Saharan Africa. *Water Economics and Policy*. 2171003, 8,1, https://doi:10.1142/S2382624X2171003X

Blomquist, W., Heikkila, T., Schlager, E. 2001. Institutions and conjunctive water management among three western states: *Natural Resources Journal*, 653-683. https://www.jstor.org/stable/24888836

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R., Jain, R., Bear, J., Schwarz, J., Wang, W., Fernandez, E. 2019. Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal*, 27(1), 1-30 https://doi.org/10.1007/s10040-018-1841-z.

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., et al. 2012. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, 120, 25–36. 10.1016/j.rse.2011.11.026

EEC (Ethiopian Engineering Cooperation). 2024. *Meki Multi-Purpose Dam Project: Agricultural planning and irrigation agronomy report*. Addis Ababa, Ethiopia, 123p.

EROS (Earth Resources Observation and Science) Center. 2020. *Landsat 8-9 Operational Land Imager and Thermal Infrared Sensor Level-2 Science Product.* U.S. Geological Survey. https://doi.org/10.5066/P9OGBGM6

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J. 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific Data*, 2(1), 150066. https://doi.org/10.1038/sdata.2015.66

Geological Survey of Ethiopia & Czech Republic Development Cooperation. 2013. *Hydrogeological maps of Ethiopia: Akaki Beseka (Sheet NC 37-14, 2013)* [Maps, 1:250,000 scale]. Geological Survey of Ethiopia.

Geological Survey of Ethiopia & Czech Republic Development Cooperation. 2019. *Hydrogeological maps of Ethiopia: Hosaina (Sheet NB 37-2, 2019)* [Maps, 1:250,000 scale]. Geological Survey of Ethiopia.

Goshime, D.W., Haile, A.T. Rientjes, T., Absi, R., Ledesert, B., Siegfried, T. 2021. Implications of water abstraction on the interconnected Central Rift Valley Lakes sub-basin of Ethiopia using WEAP. Journal of Hydrology: Regional studies 38, 100969 https://doi.org/10.1016/j.ejrh.2021.100969

Hill, M, 1998. Methods and guidelines for effective model calibration US Geological Survey Denver, CO, USA.

Hsieh, P. A., and Freckleton, J. R. 1993. *Documentation of a computer program to simulate horizontal-flow barriers using the US Geological Survey's modular three-dimensional finite-difference ground-water flow model*, US Department of the Interior, US Geological Survey.

Huete, A. R., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., Ferreira, L. G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83(1-2), 195–213. 10.1016/S0034-4257(02)00096-2

Mekonnen, K., Tadesse, M., Velpuri, N. M., Abdella, M., Dessalegn, M., Leh, M., Akpoti, K., Owusu, A., Likessa, A., Seid, A. 2026. Multi-scale assessment of irrigation water use and supply in the Amibara Irrigation Scheme, Ethiopia using Landsat-derived evapotranspiration and field data. Agricultural Water Management, 334, 110700. https://doi.org/10.1016/j.agwat.2026.110700

Ministry of Water Resources 2009. Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project Phase 2 Final Report Part II Prefeasibility Studies Integrated Watershed Management of Western Lake Ziway Sub-Basin Prefeasibility Study, Volume 2: Annexes A-K

Mwamakamba, S. N., Sibanda, L. M., Pittock, J., Stirzaker, R., Bjornlund, H., van Rooyen, A., Munguambe, P., Mdemu, M. V., Kashaigili, J. J. 2017. Irrigating Africa: Policy barriers and opportunities for enhanced productivity of smallholder farmers. *International Journal of Water Resources Development*, 33(5), 824–838. https://doi.org/10.1080/07900627.2017.1321531

Niswonger, R. G., Panday, S., Ibaraki, M. 2011. MODFLOW-NWT, a Newton formulation for MODFLOW-2005. *US Geological Survey Techniques and Methods* 6–A37, 44p. https://doi.org/10.3133/tm6A37

Rouse, J. W., Jr., Haas, R. H., Schell, J. A., Deering, D. W. 1974. *Monitoring vegetation in the Great Plains with ERTS.* In Proceedings of the Third Earth Resources Technology Satellite-1 Symposium (ERTS-1), Technical Presentations, edited by Stanley C. Freden, Enrico P. Mercanti, and Margaret A. Becker, 1, 309–317. NASA SP-351, Washington, DC.

Senay, G. B., Bohms, S., Singh, R. K., Gowda, P. H., Velpuri, N. M., Alemu, H., Verdin, J. P. 2013. Operational evapotranspiration mapping using remote sensing and weather datasets: a new parameterization for the SSEB approach. *JAWRA Journal of the American Water Resources Association*, 49(3), 577–591. https://doi.org/10.1111/jawr.12057

Senay, G. B., Friedrichs, M., Morton, C., Parrish, G. E., Schauer, M., Khand, K., Kagone, S., Boiko, O., Huntington, J. 2022. Mapping actual evapotranspiration using Landsat for the conterminous United States: Google Earth Engine implementation and assessment of the SSEBop model. *Remote Sensing of Environment*, 275, 113011. https://doi.org/10.1016/j.rse.2022.113011

Shah, N., Nachabe, M., Ross, M. 2007. Extinction depth and evapotranspiration from ground water under selected land covers. *Groundwater,* 45, 329-338. https://doi.org/10.1111/j.1745-6584.2007.00302.x

Singh, A. 2014. Conjunctive use of water resources for sustainable irrigated agriculture. *Journal of Hydrology*, 519, 1688-1697. 10.1016/j.jhydrol.2014.09.049

Smith, M., 1992. *CROPWAT: a computer program for irrigation planning and management. Land and Water Development Division*. Rome: Food and Agriculture Organization of the United Nations (FAO), Rome.

Tadesse, M., Taye, M. T., Abdella, M., Mekonnen, K., Ebrahim, G. Y., Seid A. 2026. *Enhancing Policy-Relevant Evidence for Improving Planning and Management of Smallholder Irrigation, Ethiopia.* International Water Management Institute. https://hdl.handle.net/10568/186032

Taye, M. T., Ebrahim, G. Y., Nigussie, L., Hagos, F., Uhlenbrook, S., Schmitter, P. 2022. Integrated water availability modelling to assess sustainable agricultural intensification options in the Meki catchment, Central Rift Valley, Ethiopia, *Hydrological Sciences Journal*, 67, 15, 2271-2293, https://doi.org/10.1080/02626667.2022.2138403

Taye, M. T., Ebrahim, G. Y., Mekonnen, K., Tadesse, M., Seid, A. 2026. *Current Practices and Challenges in Smallholder Irrigation Water Management: A WEFE Nexus-Based Assessment; The Case of the Meki Catchment.* International Water Management Institute (IWMI). https://hdl.handle.net/10568/182922

Tennant, D. L. 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries*, 1(4), 6–10. https://doi.org/10.1577/1548-8446(1976)001<0006:IFRFFW>2.0.CO;2

Vrba, J., Lipponen, A., Girman, J., van der Gun, J., Haie, N., Hirata, R., Lopez-Gunn, E., Neupane, B., Shah, T., and Wallin, B. 2007. *Groundwater resources sustainability indicators*. [IHP/2007/GW-14]. United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris.

Winston, R. B. 2009. "ModelMuse: a graphical user interface for MODFLOW-2005 and PHAST," US Geological Survey. http://pubs.usgs.gov/tm/tm6A29

WRC (Water Research Commission), 2023. *Conjunctive water use guideline*. WRC Report No. TT 904/22, Pretoria: Water Research Commission. Available at: https://www.wrc.org.za/wp-content/uploads/2026/06/TT-904-final-web.pdf [Accessed October 2026]

Xie H., You L., Wielgosz B., Ringler C. 2013. Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. Agricultural Water Management, 131, 183-193. 10.1016/j.agwat.2013.08.011

# Annex

## SWAT model parameters

**Annex Table 1: SWAT parameters with their fitted values and calibration ranges for streamflow at the Meki River gauging station (Meki village), calibration period 1984–1991**

| S.No. | Meki river gauged at Meki village | | | |
|---|---|---|---|---|
| | Parameter | Fitted | Minimum value | Maximum value |
| 1 | R__CN2.mgt (Avg.CN=75.34) | -0.105 | -0.2 | 0.2 |
| 2 | V__ALPHA_BF.gw | 0.048 | 0 | 1 |
| 3 | V__GW_DELAY.gw | 31 | 10 | 400 |
| 4 | V__GWQMN.gw | 1000 | 0 | 5000 |
| 5 | V__GW_REVAP.gw | 0.02 | 0.02 | 0.2 |
| 6 | V__REVAPMN.gw | 453 | 0 | 500 |
| 7 | V__RCHRG_DP.gw | 0.05 | 0 | 1 |
| 8 | V__EPCO.hru | 0.54 | 0 | 1 |
| 9 | V__ESCO.hru | 0.95 | 0 | 1 |

*R__ = relative change: V__ = replace with fitted value.*

## MODFLOW model parameters

**Annex Table 2. Calibrated aquifer hydraulic parameters by zone and layer**

| Zone | Layer | $K_h$ (m/d) | $K_v$ (m/d) | Specific yield, $S_y$ (–) | Specific storage, $S_s$ ($m^{-1}$) |
|---|---|---|---|---|---|
| 1 | 1 | 7 | 0.5 | 0.003 | $5.0 \times 10^{-6}$ |
| | 2 | 7 | 0.5 | 0.002 | $1.0 \times 10^{-6}$ |
| 2 | 1 | 0.8 | 0.2 | 0.00018 | $4.5 \times 10^{-8}$ |
| | 2 | 0.4 | 0.1 | 0.00013 | $2.0 \times 10^{-8}$ |
| 3 | 1 | 0.4 | 0.1 | 0.00016 | $5.0 \times 10^{-8}$ |
| | 2 | 0.24 | 0.06 | 0.00012 | $1.5 \times 10^{-8}$ |

| | | | | | |
|---|---|---|---|---|---|
| 4 | 1 | 0.032 | 0.008 | 0.0001 | $2.0 \times 10^{-8}$ |
| | 2 | 0.008 | 0.002 | 0.00005 | $5.0 \times 10^{-9}$ |

Note: Vertical hydraulic conductivity was set as $K_v = K_h/10$ for all zones.

**Annex Table 3. Calibrated boundary condition parameters**

| Package | Parameter | Value | Unit |
|---|---|---|---|
| Streamflow Routing (SFR) | Streambed hydraulic conductivity | 0.468 | m/d |
| | Manning's roughness coefficient | 0.03 | – |
| General Head Boundary (GHB) | Conductance | 327 | $m^2/d$ |
| Horizontal Flow Barrier (HFB) | Hydraulic characteristic (barrier hydraulic conductivity / barrier thickness) | $1 \times 10^{-4}$ | $d^{-1}$ |
| Drain (DRN) | Conductance | 5 | $m^2/d$ |



CGIAR is a global research partnership for a food-secure future. CGIAR science is dedicated to transforming food, land, and water systems in a climate crisis. Its research is carried out by 13 CGIAR Centers/Alliances in close collaboration with hundreds of partners, including national and regional research institutes, civil society organizations, academia, development organizations and the private sector. www.cgiar.org

To learn more about this and other CGIAR Research Programs, please visit:
https://www.cgiar.org/cgiar-research-portfolio-2025-2030/

**Contact**
**Meron Teferi Taye**, Researcher - Water and Climate Systems, IWMI, Addis Ababa, Ethiopia (meron.taye@cgiar.org)

CGIAR POLICY INNOVATIONS IWMI International Water Management Institute