

Validation Workshop, Capacity Building, And Technical Review Report

on

Harmonized Groundwater Recharge Estimation for IGAD Region

(Joint Regional Study – Horn of Africa Groundwater for Resilience (HoA-GW4R) Program)

Consultancy Component: Delivery 4

Prepared By:
Dr.-Ing. Sintayehu Legesse (PhD)
International Consultant

Project Reference: DJ-IGAD-36281-CS-INDV

Submitted to:
IGAD Water Programme / IGAD Secretariat

Workshop Venue:
IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, Kenya

Workshop Dates:
20–23 July 2026

Date of Submission:
August 2026

This document is prepared for the use of World Bank / IGAD and may not be reproduced or shared without permission.

Validation Workshop and Capacity Building on Harmonized Groundwater Recharge Estimation for IGAD Region Report



Workshop Participants (Photo credit: IGAD)

Project Reference: DJ-IGAD-36281-CS-IN

Submitted to:

Intergovernmental Authority on Development (IGAD)
Groundwater Unit – Horn of Africa Groundwater for Resilience Project (P174867)
IGAD Secretariat
P.O. Box 2653, Djibouti, Republic of Djibouti

Prepared by:
Dr.-Ing. Sintayehu Legesse (PhD)
International Consultant
Email: sintayehulegesse@gmail.com

ACKNOWLEDGMENT

This consultancy was conducted under the Intergovernmental Authority on Development (IGAD) and the World Bank-funded Horn of Africa Groundwater for Resilience (GW4R) Project (P174867). I sincerely acknowledge the support and collaboration of the IGAD Groundwater Unit and its technical leads.

I also appreciate the experts from IGAD Member States and workshop participants for their active engagement in the hands-on training and validation workshop. Their technical contributions and constructive feedback helped strengthen the analysis, refine the results, and ensure alignment with on-the-ground realities.

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Full Name
CHIRPS	Climate Hazards Center InfraRed Precipitation with Station Data
GEE	Google Earth Engine
HoA-GW4R	Horn of Africa Groundwater for Resilience
ICPAC	IGAD Climate Prediction and Applications Centre
IGAD	Intergovernmental Authority on Development
JRS	Joint Regional Study
PET	Potential Evapotranspiration
TM–SWB	Thornthwaite–Mather Soil Water Balance

Contents

ACKNOWLEDGMENT ..... **i**

LIST OF ACRONYMS AND ABBREVIATIONS ..... **ii**

LIST OF FIGURES ..... **vi**

EXECUTIVE SUMMARY ..... **vii**

1. INTRODUCTION **1**

2. BACKGROUND AND RATIONALE **3**

3. PURPOSE AND OBJECTIVES OF THE WORKSHOP **4**

3.1 Overall Purpose 4

3.2 Specific Objectives 4

4. PARTICIPANTS AND INSTITUTIONAL REPRESENTATION **5**

5. TRAINING AND VALIDATION APPROACH **6**

6. TRAINING PREPARATION AND TECHNICAL RESOURCES **7**

6.1 Technical Documentation 7

6.2 Training Datasets 7

6.3 Software and Computational Resources 8

6.4 Reproducibility Resources 8

7. TECHNICAL TRAINING MODULES **9**

7.1 Module I: Harmonized Empirical Groundwater Recharge Estimation 10

7.1.1 Conceptual basis of empirical recharge estimation 10

7.1.2 MacDonald et al. (2021) approach 10

7.1.3 Bredenkamp et al. (1995) approach 11

7.1.4 GIS and statistical implementation 11

7.2 Module II: Thornthwaite–Mather Soil Water Balance Method 11

8. PRACTICAL TRAINING AND HANDS-ON EXERCISES **12**

8.1 Practical Exercise I: Empirical Recharge Estimation 12

8.2 Practical Exercise II: TM–SWB Recharge Estimation 13

8.3 Spatial Analysis and Mapping 14

8.4 Model Output Visualization and Export 14

9. TECHNICAL REVIEW AND VALIDATION OF REGIONAL OUTPUTS **15**

CONTENTS

9.1 Validation of the Methodological Framework 16
9.2 Review of Input Datasets and Parameters 16
9.3 Review of Empirical Recharge Estimates 16
9.4 Review of TM–SWB Recharge Estimates 16
9.5 Review of Sensitivity and Uncertainty Analysis 17
9.6 Regional Applicability and Harmonization 17
10. GROUP DISCUSSIONS AND KNOWLEDGE EXCHANGE 18
11. WORKSHOP OUTCOMES AND CAPACITY DEVELOPMENT RESULTS 19
11.1 Technical Validation 19
11.2 Capacity Development 19
11.3 Improved Reproducibility 19
11.4 Strengthened Regional Collaboration 19
11.5 Consolidated Regional Methodology 20
12. KEY TECHNICAL RECOMMENDATIONS AND FOLLOW-UP ACTIONS 21
12.1 Institutionalization of the Harmonized Methodology 21
12.2 Continued Capacity Development 21
12.3 Regular Updating of Input Datasets 21
12.4 Strengthening Groundwater Monitoring 21
12.5 Continued Validation 21
12.6 Integration with Groundwater Management 22
12.7 Regional Data Governance 22
12.8 Development of a Sustainable Regional Technical Platform 22
13. CONCLUSIONS 23
REFERENCES 24
ANNEXES 25
Annex 1. Workshop Programme 25
Annex 2. Technical Training Manual 25
Annex 3. Geospatial Datasets 25
Annex 4. R Codes and Scripts 25
Annex 5. GEE-based Python Codes and Scripts 25
Annex 6. Workshop Participants 25

CONTENTS

Annex 7. Workshop Photographs and Documentation 26
Annex 8. Technical Validation and Feedback Matrix 27

LIST OF FIGURES

Figure 1: Integrated framework linking technical training, practical implementation, validation, and refinement of the regional groundwater recharge products 6
Figure 2: Integrated framework linking technical training, practical implementation, validation, and refinement of the regional groundwater recharge products 9
Figure 3: Workflow of the empirical method for spatial groundwater recharge estimation 10
Figure 4: Conceptual Representation of Hydrological Processes Controlling Groundwater Recharge 11
Figure 5: TM–SWB Modelling and GEE Implementation Workflow 13
Figure 6: Regional groundwater recharge methodology review, assessment, quality assurance, validation, and harmonization framework 15

EXECUTIVE SUMMARY

The Joint Regional Study (JRS) on Harmonized Regional Groundwater Recharge Estimation for the IGAD Region, under the Horn of Africa–Groundwater for Resilience (HoA-GW4R) Program, aims to establish a scientifically robust and reproducible framework for regional groundwater recharge assessment. As a key consultancy milestone, a Regional Technical Hands-on Training and Validation Workshop was conducted at the IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, Kenya, from 20–23 July 2026.

The workshop brought together groundwater, hydrology, GIS, remote sensing,IT and water-resources experts from Djibouti, Ethiopia, Kenya, Somalia, Uganda, South Sudan, and Sudan, together with representatives of IGAD and ICPAC. The programme combined technical training, hands-on implementation, technical validation, and regional knowledge exchange.

The training covered two complementary recharge estimation approaches. The harmonized empirical methods were implemented using R programming and QGIS for computation, spatial analysis, visualization, and mapping. The Thornthwaite–Mather Soil Water Balance (TM–SWB) method was implemented using Google Earth Engine (GEE) and Python scripting. Participants worked directly with standardized climate, soil, root-zone, and spatial datasets, progressing from data preparation and model implementation to recharge-map generation and interpretation.

The training was followed by a technical review and validation of the regional groundwater recharge methodologies and outputs. Participants assessed the methods, datasets, parameters, assumptions, spatial patterns, differences between approaches, and sensitivity and uncertainty considerations. The workshop also facilitated exchange of national groundwater assessment experience and strengthened regional understanding of harmonized recharge estimation.

Importantly, the technical comments, observations, and recommendations from participants were incorporated, as appropriate, into the refinement of the final groundwater recharge assessment, maps, datasets, methodology, and supporting consultancy documentation, strengthening their scientific quality, consistency, and regional applicability.

The training concluded with the award of certificates to each participating expert, formally recognizing completion of the technical capacity-building programme. Overall, the workshop strengthened regional technical capacity, validated the principal consultancy outputs, and established a practical foundation for continued application of the harmonized recharge methodology across IGAD Member States.

1. INTRODUCTION

Groundwater is a critical component of water security, climate resilience, ecosystem sustainability, and socioeconomic development across the Horn of Africa. However, the assessment and management of groundwater resources remain constrained by substantial spatial and temporal variability in climate, hydrogeology, soil characteristics, land cover, topography, and groundwater–surface water interactions. These challenges are further compounded by differences in data availability, methodological approaches, institutional capacities, and groundwater monitoring systems among countries in the region.

In response to these challenges, the Horn of Africa – Groundwater for Resilience (HoA-GW4R) Program, implemented within the framework of the Joint Regional Study (JRS**)**, supports the development of harmonized approaches for assessing groundwater resources across the IGAD region.

One of the major technical components of the consultancy has been the development and application of harmonized groundwater recharge estimation methodologies capable of producing consistent, spatially explicit, and technically reproducible estimates across the IGAD region. Two complementary approaches were adopted:

1. **Harmonized empirical groundwater recharge estimation methods**, including the approaches of MacDonald et al. (2021) and Bredenkamp et al. (1995); and
2. **The Thornthwaite–Mather Soil Water Balance (TM–SWB) method**, implemented using geospatial and cloud-computing technologies, particularly Google Earth Engine (GEE).

Successfully implementing these approaches required not only methodological development but also technical review, stakeholder consultation, validation, knowledge transfer, and capacity development among groundwater and water-resource professionals in IGAD Member States.

Accordingly, a **Validation Workshop and Hands-on Technical Training** was conducted at the **IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, Kenya, from 20 to 23 July 2026**.

The workshop represented a key milestone in the consultancy, bringing together groundwater, hydrology, GIS, remote sensing, and water-resources experts from the IGAD Member States, together with representatives of IGAD, ICPAC, the Joint Regional Study team, and relevant national institutions. It provided a structured platform to strengthen technical capacity through hands-on training, demonstrate the application of the harmonized recharge methodologies,

review and validate the regional recharge outputs, facilitate regional knowledge exchange, and incorporate expert feedback into the final consultancy deliverables.

Accordingly, the workshop served three interconnected functions:

- **Technical capacity building** through theoretical and hands-on training in empirical and TM–SWB groundwater recharge estimation using R, QGIS, Python, and Google Earth Engine;
- **Technical review and validation** of the harmonized methodologies, input datasets, parameters, assumptions, and regional recharge outputs; and
- **Regional knowledge exchange and consensus building**, generating technical comments and recommendations that strengthened the scientific quality, consistency, regional applicability, and practical utility of the final groundwater recharge assessment and associated consultancy outputs.

Further information on the training activity and programme is available through the IGAD Water Programme:

IGAD Water Programme – Groundwater Recharge Training

2. BACKGROUND AND RATIONALE

Groundwater recharge represents the process through which water from precipitation and other surface sources infiltrates through the soil and unsaturated zone and reaches the saturated groundwater system. Its magnitude and spatial distribution are controlled by a complex combination of precipitation, evapotranspiration, soil properties, vegetation, land use, root-zone characteristics, topography, geological conditions, and hydrological processes.

Reliable estimation of recharge is consequently essential for:

- groundwater resource assessment;
- groundwater development planning;
- drought and climate-resilience planning;
- groundwater–surface water interaction assessment;
- managed aquifer recharge planning;
- water allocation and resource management;
- ecosystem and environmental-flow assessment; and
- long-term water-security planning.

Despite its importance, direct measurement of groundwater recharge remains difficult and expensive at regional scales. Consequently, indirect and modelling-based approaches are widely used. However, differences in datasets, spatial resolution, assumptions, equations, parameterization, and implementation procedures can result in substantially different recharge estimates.

The IGAD region presents an additional challenge because it encompasses highly diverse climatic and hydrogeological environments, ranging from humid and sub-humid highlands to semi-arid and arid lowlands. A methodology developed for one hydroclimatic environment may therefore not be directly transferable to another without appropriate harmonization.

The JRS therefore emphasized the development of a consistent regional methodology, supported by standardized datasets, reproducible computational procedures, common spatial resolutions, transparent assumptions, and clearly documented workflows.

The Validation Workshop was organized to ensure that the resulting methodology was not only technically defensible but also understandable and practically applicable by national experts.

3. PURPOSE AND OBJECTIVES OF THE WORKSHOP

3.1 Overall Purpose

The overall purpose of the workshop was to provide a structured regional platform for the technical validation, review, demonstration, and transfer of the harmonized groundwater recharge estimation methodologies and regional products developed under the JRS consultancy.

3.2 Specific Objectives

The workshop pursued the following specific objectives:

1. To present the harmonized groundwater recharge estimation framework developed under the consultancy.
2. To technically review and validate the selected empirical recharge estimation approaches.
3. To demonstrate the implementation of the TM–SWB method using standardized regional datasets.
4. To present and review the resulting regional groundwater recharge maps and databases.
5. To provide hands-on training in R, QGIS, Python, and Google Earth Engine.
6. To strengthen the capacity of technical experts from IGAD Member States to reproduce and apply the methodologies.
7. To promote a common understanding of the assumptions, strengths, limitations, and uncertainties associated with recharge estimation.
8. To facilitate exchange of national and regional groundwater assessment experience.
9. To collect technical comments and recommendations from participating experts.
10. To incorporate relevant feedback into the final consultancy outputs.
11. To establish a practical foundation for continued regional application and updating of groundwater recharge products.

4. PARTICIPANTS AND INSTITUTIONAL REPRESENTATION

The workshop brought together groundwater, hydrology, GIS, remote sensing, climate, and water-resource management professionals representing IGAD Member States and regional institutions.

The participants included technical experts from:

- IGAD;
- national water-sector institutions of IGAD Member States;
- other relevant technical and development partners.

Regional scientists from **Djibouti, Sudan, South Sudan, and Uganda** and technical experts and representatives from the Ministries of Water of **Kenya, Ethiopia, and Somalia** actively participated in the technical review and validation discussions.

The multidisciplinary composition of the participants was particularly important because groundwater recharge estimation requires integration of hydrogeology, hydrology, climatology, soil science, GIS, remote sensing, and computational modelling.

5. TRAINING AND VALIDATION APPROACH

The workshop adopted an integrated **presentation–demonstration–hands-on practice–group review–validation** approach.

Rather than treating capacity building and validation as separate activities, the workshop used practical implementation as a mechanism for technical verification. Participants were therefore able to examine the methodology while simultaneously reproducing selected processing steps and evaluating the resulting outputs.

The overall approach can be summarized as follows (Figure 1):

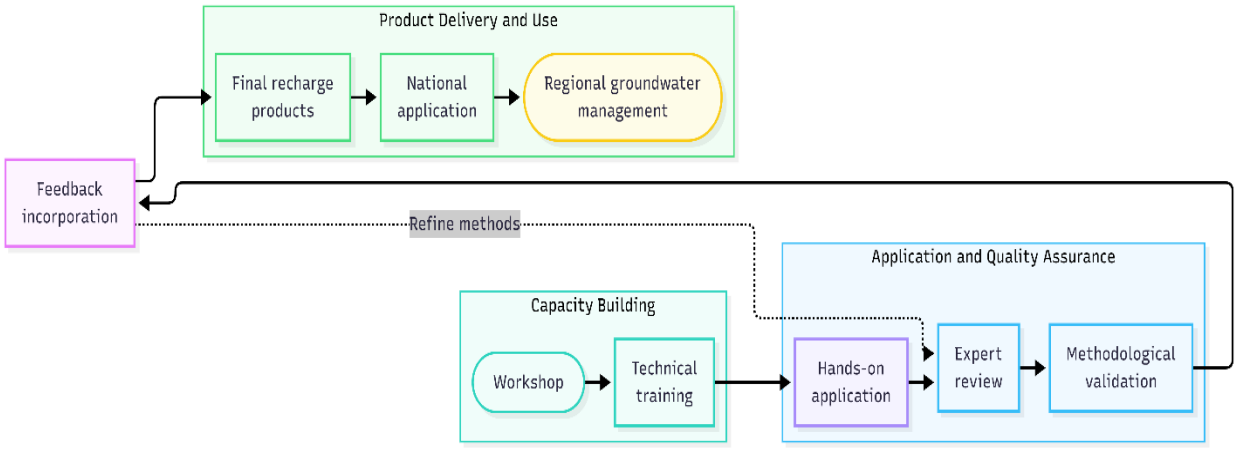


Figure 1: Integrated framework linking technical training, practical implementation, validation, and refinement of the regional groundwater recharge products

This approach ensured that participants understood not only **what** was calculated but also **why** particular datasets, equations, parameters, spatial resolutions, and processing procedures were used.

6. TRAINING PREPARATION AND TECHNICAL RESOURCES

Comprehensive preparation was undertaken before the workshop to ensure that participants could directly reproduce the methodologies during the practical sessions.

The training package consisted of four main components:

6.1 Technical Documentation

The technical documentation was developed to provide a comprehensive and practical reference for the application, interpretation, and further use of the groundwater recharge assessment methods. It included detailed descriptions of the methodologies and their theoretical background, together with the key assumptions and limitations associated with their application. The documentation also defined the parameters used in the analyses and identified the relevant data sources, including the procedures followed for data preparation and preprocessing. In addition, the modelling workflows were documented in a clear and reproducible manner, covering the major steps from input-data preparation through model implementation and output generation. Validation procedures and interpretation guidance were also provided to support the assessment of model results and their appropriate use in groundwater resource planning and management. Finally, troubleshooting guidance was included to assist users in identifying and resolving common technical, data, and modelling issues during subsequent application and updating of the assessment framework.

6.2 Training Datasets

Standardized datasets were prepared, harmonized, and distributed to support the consistent application of the groundwater recharge assessment methodology across the IGAD region. The datasets included IGAD regional and national administrative boundaries, precipitation datasets including CHIRPS precipitation data, potential evapotranspiration datasets, soil property and soil hydraulic characteristic datasets, and effective root-zone depth datasets. Where applicable, land-cover and other relevant spatial datasets were also prepared and standardized. In addition, reference and validation datasets, together with supporting GIS layers, were compiled and distributed to facilitate model implementation, spatial analysis, validation, visualization, and subsequent updating of the regional groundwater recharge assessment.

6.3 Software and Computational Resources

The training utilized a range of open-source and established geospatial, statistical, and computational tools to support the practical application of the groundwater recharge assessment methodologies. These included R and RStudio for statistical analysis, data processing, and visualization; QGIS and, where relevant, ArcGIS for geospatial processing, spatial analysis, and map production; Python for data processing, analysis, and automation; and Google Earth Engine (GEE) for cloud-based processing and implementation of the remote sensing and water-balance modelling workflows. Relevant packages, libraries, scripts, and supporting computational resources were also used to facilitate reproducible analysis and enable participants to apply, adapt, and update the developed workflows in subsequent applications.

6.4 Reproducibility Resources

To support post-workshop application and continued institutional use of the methods, participants were provided with a comprehensive training resource package comprising R scripts, Python scripts, Google Earth Engine (GEE) scripts, QGIS project files, practical exercise files, example input datasets, processed output datasets, and accompanying technical instructions. The package was designed to enable participants to reproduce the training exercises, apply the developed methodologies using their own datasets, and adapt the workflows to national and institutional requirements. By providing the scripts, project files, datasets, and supporting documentation together, the resource package also facilitates knowledge transfer, technical continuity, and independent application of the groundwater recharge assessment framework beyond the completion of the workshop.

7. TECHNICAL TRAINING MODULES

The technical training was organized around two complementary groundwater recharge estimation approaches (Figure 2).

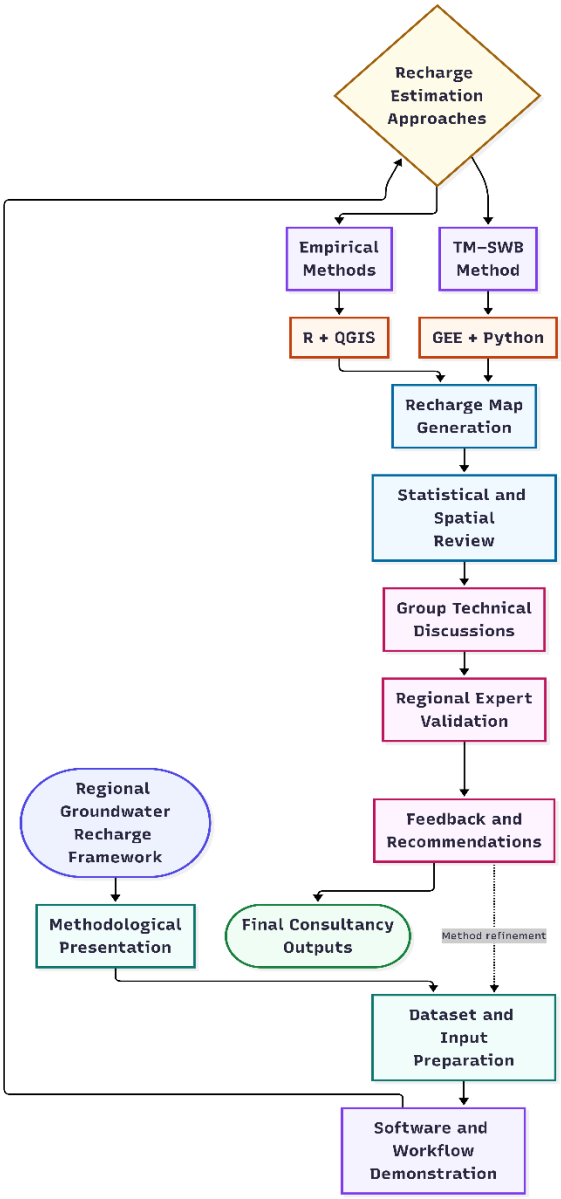


Figure 2: Integrated framework linking technical training, practical implementation, validation, and refinement of the regional groundwater recharge products

7.1 Module I: Harmonized Empirical Groundwater Recharge Estimation

The first module introduced participants to the principles and application of empirical groundwater recharge estimation (Figure 3).

The module covered:

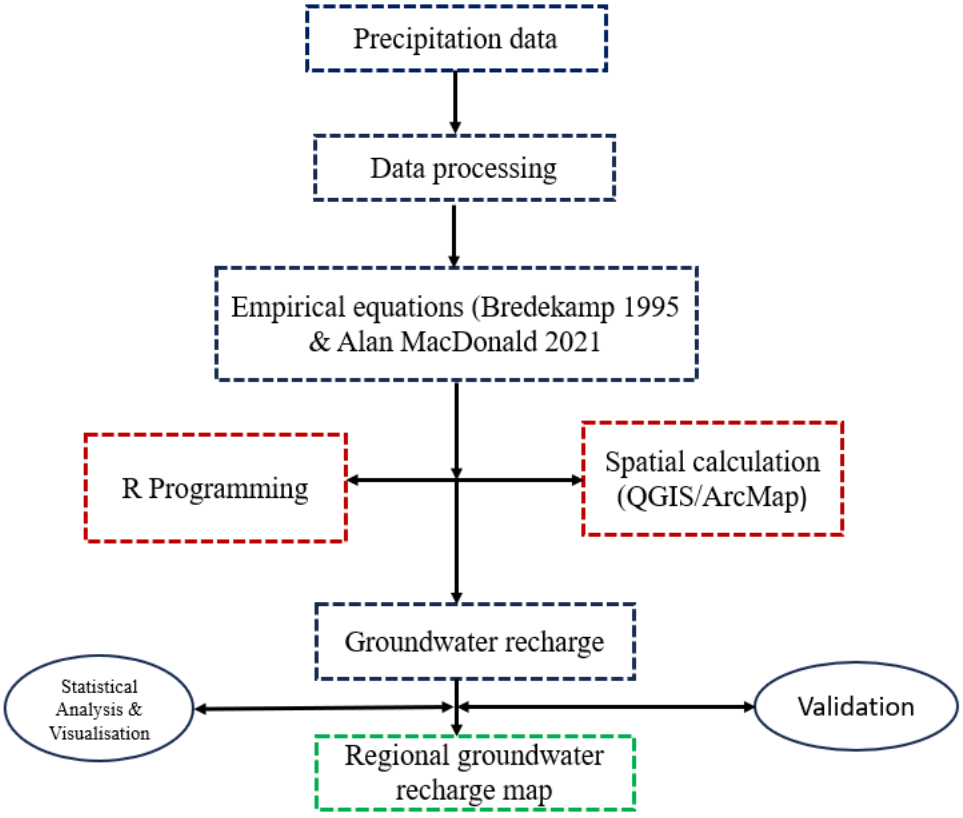


Figure 3: Workflow of the empirical method for spatial groundwater recharge estimation

7.1.1 Conceptual basis of empirical recharge estimation

Participants were introduced to the relationship between precipitation and groundwater recharge and to the factors influencing the proportion of precipitation that ultimately becomes recharge.

7.1.2 MacDonald et al. (2021) approach

The training covered the conceptual and mathematical basis of the groundwater recharge equation developed by MacDonald et al. (2021), including the required input variables, interpretation of key parameters, equation implementation, spatial application, underlying assumptions, and methodological limitations.

7.1.3 Bredenkamp et al. (1995) approach

The Bredenkamp et al. (1995) recharge estimation approach was similarly introduced and implemented, with particular attention to input requirements, parameterization, spatial implementation, comparison with alternative empirical approaches, and interpretation of the estimated recharge.

7.1.4 GIS and statistical implementation

The GIS and statistical implementation module provided hands-on training on precipitation data preparation, organization of spatial input layers, implementation of recharge equations in R, generation of raster-based recharge estimates, statistical summarization, visualization of spatial variability, and export of regional recharge products. The module emphasized reproducibility, standardization, and consistency to enable the same workflow to be applied across IGAD Member States.

7.2 Module II: Thornthwaite–Mather Soil Water Balance Method

The second module focused on the Thornthwaite–Mather Soil Water Balance (TM–SWB) method, which provides a more process-oriented assessment of groundwater recharge by explicitly accounting for water movement and partitioning within the soil–plant–atmosphere system. The training covered precipitation, potential evapotranspiration, soil water storage and deficit, actual evapotranspiration, soil water-holding capacity, effective root-zone depth, excess water, and groundwater recharge. The method was implemented using Google Earth Engine (GEE) and Python, enabling consistent regional-scale processing of spatially distributed datasets.

Particular emphasis was placed on understanding how changes in precipitation, evapotranspiration, soil properties, and effective root-zone depth influence estimated recharge (Figure 4).

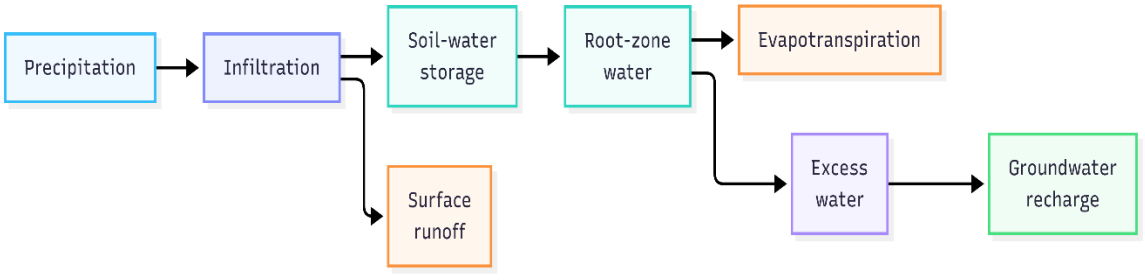


Figure 4: Conceptual Representation of Hydrological Processes Controlling Groundwater Recharge

8. PRACTICAL TRAINING AND HANDS-ON EXERCISES

The practical sessions were designed to move participants progressively from basic data visualization to complete regional recharge estimation.

8.1 Practical Exercise I: Empirical Recharge Estimation

The first practical exercise involved implementation of the harmonized empirical recharge methods.

The workflow included:

1. Opening and inspecting precipitation datasets.
2. Importing regional and national boundaries.
3. Displaying administrative boundaries and reference locations.
4. Preparing raster datasets.
5. Checking spatial extent, projection, resolution, and data quality.
6. Implementing the selected recharge equations in R.
7. Executing recharge calculations.
8. Generating spatially distributed recharge estimates.
9. Producing descriptive statistics.
10. Comparing recharge estimates from different empirical methods.
11. Preparing thematic recharge maps.
12. Exporting final raster products.

Participants worked individually and in groups to reproduce selected regional recharge outputs.

Technical discussions were subsequently conducted on:

- spatial patterns of recharge;
- magnitude and range of estimated recharge;
- differences between empirical approaches;
- hydroclimatic controls;
- uncertainty;
- applicability at national scale; and
- implications for groundwater resource assessment.

8.2 Practical Exercise II: TM–SWB Recharge Estimation

The second practical exercise involved implementation of the TM–SWB method using Google Earth Engine and Python (Figure 5).

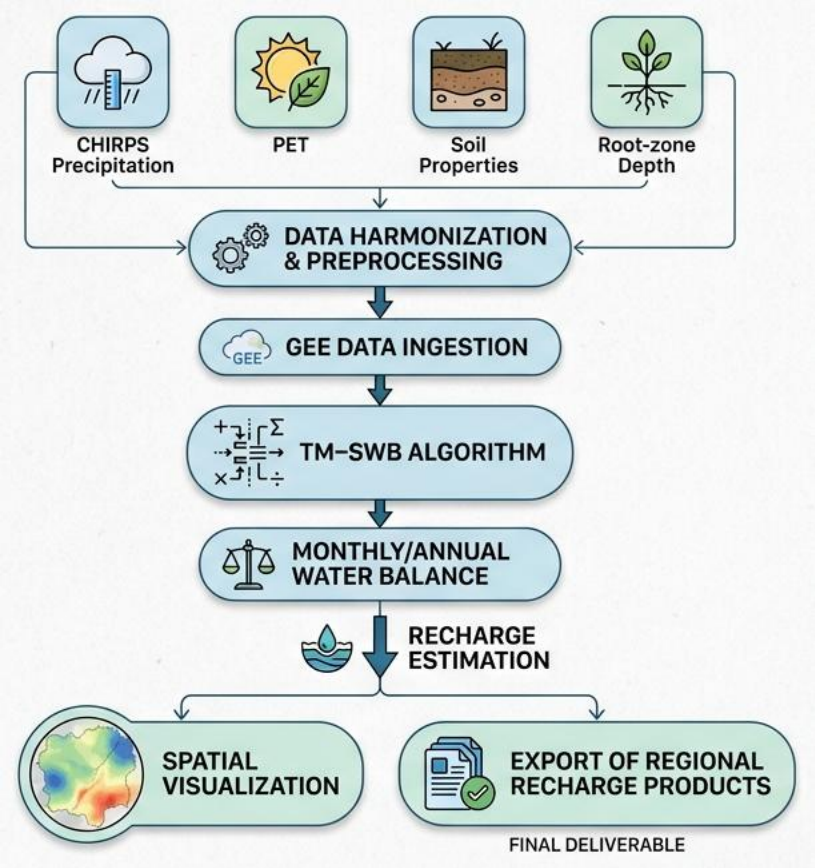


Figure 5: TM–SWB Modelling and GEE Implementation Workflow

The practical workflow included:

1. Establishing and configuring a Google Earth Engine project.
2. Preparing the Python environment.
3. Importing and organizing regional datasets.
4. Accessing cloud-hosted Earth Observation and climate datasets.
5. Preparing precipitation data.
6. Preparing potential evapotranspiration data.
7. Preparing soil hydraulic property datasets.
8. Defining effective root-zone depth.
9. Establishing soil water balance parameters.
10. Implementing the TM–SWB algorithm.
11. Executing the model using cloud-based processing.

12. Generating annual recharge estimates.
13. Visualizing spatial recharge patterns.
14. Assessing output statistics.
15. Exporting recharge products.

The exercise emphasized the scientific rationale behind every major model input.

8.3 Spatial Analysis and Mapping

GIS-Based Visualization and Mapping

GIS-based visualization and mapping constituted an important component of the practical training, providing participants with the skills required to interpret and communicate groundwater recharge information in a spatially meaningful manner. Participants were trained to display and manage raster and vector datasets, overlay administrative boundaries, examine spatial patterns and variations, and compare different groundwater recharge products. The exercises also focused on identifying areas with relatively high and low estimated recharge, preparing professional map layouts, applying appropriate legends and classification schemes, and exporting publication- and report-ready maps. Through these practical GIS exercises, participants gained experience in transforming model outputs and recharge estimates into clear and interpretable spatial information that can be used to support groundwater assessment, planning, resource management, and evidence-based decision-making at national and regional levels.

8.4 Model Output Visualization and Export

Participants were also trained in preparing standardized recharge outputs, including annual groundwater recharge maps, recharge statistics, spatial summaries, comparison maps, raster and tabular datasets, and visualization products.

Standardized naming, projection, spatial resolution, and metadata procedures were emphasized to facilitate regional data integration.

9. TECHNICAL REVIEW AND VALIDATION OF REGIONAL OUTPUTS

The technical validation component constituted a central part of the workshop.

The objective was not simply to obtain general acceptance of the outputs but to systematically examine the methodological assumptions, datasets, parameters, computational implementation, spatial consistency, and practical applicability of the regional recharge products (Figure 6).

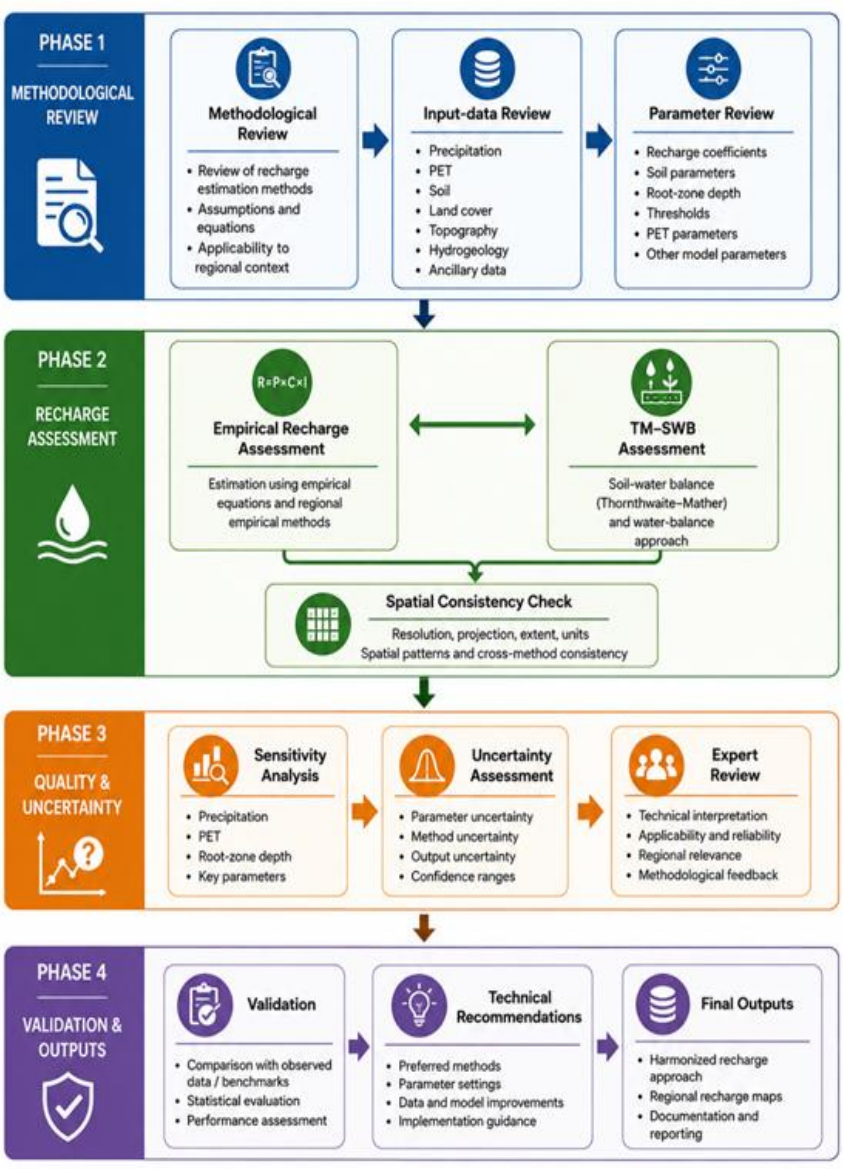


Figure 6: Regional groundwater recharge methodology review, assessment, quality assurance, validation, and harmonization framework

9.1 Validation of the Methodological Framework

Participants reviewed the overall methodological framework, focusing on the scientific justification and regional suitability of the selected approaches, consistency of input datasets, transparency of assumptions, reproducibility of the workflow, treatment of spatial variability and uncertainty, and compatibility with national groundwater assessment activities. The discussions confirmed the value of applying complementary empirical and soil water balance approaches rather than relying on a single recharge estimation method.

9.2 Review of Input Datasets and Parameters

Participants reviewed the principal input datasets used in the regional modelling framework, with particular attention to precipitation, potential evapotranspiration, soil properties, soil water-holding characteristics, root-zone depth, spatial resolution, temporal coverage, data consistency, and regional representativeness. The discussions emphasized the importance of maintaining consistent input datasets across national boundaries to minimize artificial discontinuities in regional recharge estimates.

9.3 Review of Empirical Recharge Estimates

The harmonized empirical recharge outputs were presented and examined from both regional and country-specific perspectives. Participants reviewed the spatial patterns and magnitude of estimated recharge, their consistency with climatic and broad hydrogeological conditions, differences among empirical equations, areas requiring further investigation, and potential applications of the outputs. The discussions highlighted the importance of interpreting empirical recharge estimates in relation to the environmental conditions and methodological assumptions underlying each approach.

The comparison demonstrated the importance of interpreting empirical recharge estimates in relation to the environmental conditions and assumptions underlying each method.

9.4 Review of TM–SWB Recharge Estimates

The TM–SWB outputs were reviewed with particular attention to the spatial behaviour of recharge under different climatic and environmental conditions.

Participants examined the influence of precipitation, evapotranspiration, soil water storage, effective root-zone depth, and their effects on the spatial distribution and seasonal and annual variability of recharge. The discussion also considered the consistency and plausibility of model behaviour across different environmental conditions.

The review emphasized that soil-water-balance recharge estimates should be interpreted as model-derived estimates subject to input-data and parameter uncertainties rather than as direct observations of groundwater flux.

9.5 Review of Sensitivity and Uncertainty Analysis

Sensitivity analysis was presented as an important component of assessing the robustness of the recharge estimates. The analysis examined the response of estimated recharge to changes in key model parameters, including precipitation, potential evapotranspiration, and effective root-zone depth. Results showed that recharge estimates were particularly sensitive to variations in precipitation and evapotranspiration, with the magnitude and direction of response varying spatially according to climatic and soil-water conditions.

The sensitivity assessment supported identification of influential parameters, improved understanding of uncertainty, strengthened interpretation of regional recharge patterns, informed priorities for future data improvement, and provided guidance on the appropriate use and interpretation of the recharge products.

9.6 Regional Applicability and Harmonization

A key outcome of the technical review was the confirmation of the importance of maintaining a common regional methodology. Participants recognized that the harmonization framework provides a valuable basis for cross-border groundwater assessment, regional comparison, transboundary aquifer assessment, groundwater planning, drought and climate-resilience planning, identification of groundwater recharge zones, and future updating of the regional recharge database.

The workshop further emphasized that harmonization does not imply that recharge processes are uniform across the region. Rather, it provides a common methodological and data framework through which spatial and environmental differences can be consistently represented, compared, and interpreted.

10. GROUP DISCUSSIONS AND KNOWLEDGE EXCHANGE

Interactive group discussions were integrated throughout the workshop, providing participants with an opportunity to share national experiences related to groundwater occurrence, hydrogeological conditions, rainfall variability, recharge mechanisms, groundwater monitoring and abstraction, recharge estimation methods, data availability, modelling challenges, and institutional capacity. The discussions enabled participants to compare the regional methodology with existing national practices and highlighted the importance of strengthening cooperation among IGAD Member States, particularly where groundwater systems cross national boundaries or climate and hydrological processes have regional characteristics. The exchange of practical experience was therefore an important component of the workshop's capacity-building outcomes.

11. WORKSHOP OUTCOMES AND CAPACITY DEVELOPMENT RESULTS

The workshop achieved the principal objectives established for the validation and capacity-building activity.

11.1 Technical Validation

The harmonized groundwater recharge estimation framework and associated regional products were presented for expert review. Technical discussions provided constructive feedback on the methodology, input data, parameters, model assumptions, spatial consistency, interpretation, uncertainty, and regional applicability. Relevant recommendations and clarifications were incorporated into the refinement of the final consultancy outputs.

11.2 Capacity Development

Participants gained practical experience in groundwater recharge estimation, empirical recharge equations, soil water balance modelling, R programming, QGIS, Python, Google Earth Engine, raster processing, spatial analysis, recharge mapping, and interpretation of model outputs. The hands-on approach enabled participants to reproduce key analytical steps and workflows rather than relying solely on demonstrations, thereby strengthening practical capacity for independent application.

11.3 Improved Reproducibility

The provision of standardized datasets, scripts, project files, and training manuals created a foundation for continued application of the methodology after the workshop.

The resulting training package provides an operational bridge between the regional methodology and future national implementation.

11.4 Strengthened Regional Collaboration

The workshop created an important forum for technical interaction among groundwater and water-resource professionals from IGAD Member States.

The exchange of national experiences strengthened understanding of regional groundwater challenges and reinforced the need for continued technical cooperation.

11.5 Consolidated Regional Methodology

The workshop contributed to establishing a common methodological framework for regional groundwater recharge estimation, combining standardized datasets, harmonized methods, reproducible computational workflows, GIS-based spatial analysis, cloud-based processing, validation and expert review, and uncertainty and sensitivity assessment.

12. KEY TECHNICAL RECOMMENDATIONS AND FOLLOW-UP ACTIONS

Based on the technical discussions and validation process, the following actions are recommended.

12.1 Institutionalization of the Harmonized Methodology

The harmonized recharge estimation framework should be maintained as a common technical reference for future regional groundwater assessments under IGAD.

12.2 Continued Capacity Development

Additional national and regional training should be considered to strengthen participants' practical capacity in R, Python, Google Earth Engine, QGIS, groundwater recharge modelling, and spatial data management.

12.3 Regular Updating of Input Datasets

The regional recharge products should be periodically updated as improved climate, soil, land-cover, and hydrogeological datasets become available.

12.4 Strengthening Groundwater Monitoring

Model-derived recharge estimates should progressively be supported by improved groundwater monitoring and field-based observations. Priority should be given to groundwater-level and spring monitoring, streamflow and rainfall observations, groundwater abstraction monitoring, and targeted field investigations of recharge processes.

12.5 Continued Validation

Validation should be treated as an ongoing process rather than a one-time activity. As additional observations become available, the recharge estimates should be reassessed and, where necessary, recalibrated or refined.

12.6 Integration with Groundwater Management

The regional recharge products should be progressively integrated into groundwater availability and abstraction planning, aquifer vulnerability assessment, drought monitoring and early warning, climate-change impact assessment, groundwater-dependent ecosystem assessment, and transboundary aquifer management. This integration will enhance the practical value of the recharge estimates for evidence-based groundwater planning and sustainable regional water resources management.

12.7 Regional Data Governance

A clear institutional arrangement should be established for the long-term management and maintenance of the regional groundwater recharge database. The arrangement should define responsibilities for data ownership, regular updating, quality control, metadata management, version control, data access, and sustained maintenance and updating of the regional recharge products.

12.8 Development of a Sustainable Regional Technical Platform

The tools and scripts developed under the consultancy should be maintained as a reusable regional technical platform rather than treated as one-time consultancy outputs.

13. CONCLUSIONS

The Validation Workshop and Hands-on Technical Training conducted at the IGAD Climate Prediction and Applications Centre (ICPAC), Nairobi, from 20–23 July 2026, constituted a major milestone in the Joint Regional Study on harmonized groundwater recharge estimation under the Horn of Africa – Groundwater for Resilience (HoA-GW4R) Program.

The workshop successfully integrated **technical validation, practical capacity building, methodological harmonization, knowledge exchange, and stakeholder consultation**.

The two complementary recharge estimation approaches, the harmonized empirical methods and the Thornthwaite–Mather Soil Water Balance method, were presented, demonstrated, implemented, and critically reviewed by participating experts.

The hands-on training strengthened participants' practical capacity in R, QGIS, Python, and Google Earth Engine and enabled them to reproduce key components of the regional recharge assessment workflow.

The technical review further provided an opportunity to examine the assumptions, input datasets, parameterization, spatial implementation, sensitivity, uncertainty, and regional applicability of the developed methodologies. Constructive comments and recommendations from participants contributed to refinement of the final consultancy products.

Overall, the workshop demonstrated that the developed framework provides a transparent, reproducible, and regionally harmonized basis for estimating groundwater recharge across the IGAD region. At the same time, the discussions emphasized that recharge estimates should be interpreted within the context of model assumptions, input-data limitations, hydrogeological variability, and uncertainty.

The workshop therefore represents not only a validation activity but also an important step toward establishing a **sustainable regional technical capacity and common methodological foundation for groundwater assessment and management in the Horn of Africa**.

The combination of harmonized methods, standardized datasets, reproducible codes, GIS workflows, cloud-based processing, and trained national experts provides a strong foundation for future groundwater assessment, climate-resilience planning, and evidence-based water-resource management across IGAD Member States.

REFERENCES

Bredenkamp, D. B. (1995). *Manual on quantitative estimation of groundwater recharge and aquifer storativity: Based on practical hydrological methods* (TT 73/95). Water Research Commission.

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*, 150066. https://doi.org/10.1038/sdata.2015.66

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment, 202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

MacDonald, A. M., Lark, R. M., Taylor, R. G., Abiye, T., Fallas, H. C., Favreau, G., Goni, I. B., Kebede, S., Scanlon, B., Sorensen, J. P. R., Tijani, M., Upton, K. A., & West, C. (2021). Mapping groundwater recharge in Africa from ground observations and implications for water security. *Environmental Research Letters*, *16*(3), 034012. https://doi.org/10.1088/1748-9326/abd661

QGIS Development Team. (2026). *QGIS Geographic Information System* (Version 3.44). QGIS Association. https://www.qgis.org

R Core Team. (2025). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Thornthwaite, C. W., & Mather, J. R. (1957). *Instructions and tables for computing potential evapotranspiration and the water balance*. Drexel Institute of Technology, Laboratory of Climatology.

Posit Team. (2025). *RStudio: Integrated development environment for R*. Posit Software, PBC. https://posit.co/

ANNEXES

The technical resources developed and used during the workshop are incorporated into this validation and technical training report as supporting annexes.

Annex 1. Workshop Programme

The complete training workshop agenda and daily programme are available on the IGAD Water unit website (https://water.igad.int/Training_gw_recharge)

Annex 2. Technical Training Manual

The complete hands-on training manual is attached as a standalone annex.

Annex 3. Geospatial Datasets

The geospatial data package used for the training is attached as a standalone annex.

Annex 4. R Codes and Scripts

This R script-based empirical model is attached as a standalone annex.

Annex 5. GEE-based Python Codes and Scripts

Script code used in the training for the soil water balance method to estimate groundwater script and code used during the training to estimate groundwater recharge using the Soil Water Balance method, are provided as a standalone annex.

Annex 6. Workshop Participants

List of Participants

No	Name	Position	Country
1	Dr.Maha Abdegaffar Abdelerahim Ismail	Regional Expert	Sudan
2	Dr.Abdoulrahman Houmed Gaba	Regional Expert	Djibouti
3	Mr.Deng Santino	Regional Expert	South Sudan
4	Dr.Hellen Aluku	Regional Expert	Uganda
5	Mr. Solomon Kenea	National Expert	Ethiopia

6	Mr.Feyessa Kabeto	National Expert	Ethiopia
7	Ms.Farhia Ahmed Abdulahi	National Expert	Somali
9	Mr.Mohamed Abdulkadir Mohamed	National Expert	Somali
10	Mr.Awies Abdinur Ahmed	National Expert	Somali
11	Mr.Mohammed Mukhtar Muallim	National Expert	Somali
12	Dr.Okoth Owuor	National Expert	Kenya
13	Ms.Margaret Irungu	National Expert	Kenya
14	Ms.Joline Acheing	National Expert	Kenya
15	Dr.Samson Oiro	National Expert	Kenya
16	Mr.Charles Kioko	National Expert	Kenya

Annex 7. Workshop Photographs and Documentation

Selected photos from the validation and training workshop








Figure 1a. Participants attending the validation and hands-on training workshop at ICPAC, Kenya, 20–23 July 2026. Photo credit: *IGAD/ICPAC Communication Officer*.

Annex 8. Technical Validation and Feedback Matrix

A consolidated matrix is included showing:

Table 1a: Technical validation feedback matrix

No.	Issue / Comment	Source / Participant	Technical Response	Action Taken	Status
1	Methodological approach	Workshop participants	Methodological basis, assumptions, and applicability were reviewed.	Method refined and documented.	Addressed
2	Spatial availability and variability	Workshop participants	Spatial recharge patterns were assessed against expert knowledge and field experience.	Spatial interpretation strengthened.	Addressed
3	Expert/ground-based interpretation	Workshop participants	Ground knowledge was considered in interpreting recharge patterns.	Expert observations incorporated into interpretation.	Addressed
4	Input datasets and quality	Workshop participants	Dataset coverage, resolution, consistency, and suitability were reviewed.	Data processing and harmonization documented.	Addressed

5	Parameter selection	Workshop participants	Key parameters and assumptions were reviewed and justified.	Parameter justification strengthened.	Addressed
6	Sensitivity analysis	Workshop participants	Sensitivity of recharge estimates to key inputs and parameters was assessed.	Sensitivity results incorporated.	Addressed
7	Validation approach	Workshop participants	Validation procedures, reference data, and performance were clarified.	Validation analysis and limitations documented.	Addressed
8	Spatial consistency	Workshop participants	Recharge patterns were checked against hydro-climatic and groundwater conditions.	Spatial consistency assessment incorporated.	Addressed
9	Mapping and visualization	Workshop participants	Recharge maps were reviewed for clarity and practical interpretation.	Maps and visualization refined.	Addressed
10	Uncertainty and applicability	Workshop participants	Key uncertainties and practical uses of the recharge layer were discussed.	Uncertainty and application guidance documented.	Addressed