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College of Technology and Built Environment (CTBE)

School of Civil and Environmental Engineering

(Major in Hydraulic)

Performance Evaluation of Karfe Small-Scale Irrigation Scheme:
(A case Study of Karfe Small Scale Irrigation Scheme East Shoa Bishoftu, Ethiopia)

A thesis submitted and presented to the school of graduate studies of Addis Ababa University in partial fulfilment of the degree of Masters of Science in School of Civil and Environmental Engineering (Major in Hydraulic Engineering).

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COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT (CTBE) SCHOOL OF GRADUATE STUDIES

Performance Evaluation of a Small-Scale Irrigation Scheme: A Case Study of the Karfe Small-Scale Irrigation Scheme, East Shoa Zone, Bishoftu, Ethiopia

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfilment of the Requirements for the Degree of Master of Science in Civil and Environmental Engineering. (Hydraulic Engineering Stream)

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Declaration

I, Enanye Tadege, hereby declare that this thesis is my own original work and carried out independently. I confirm that it has not been submitted previously, in whole or in qualification. All sources of this work data, information, material and methods in this research have been properly acknowledged in accordance with accepted in practice.

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Abstract

The performance of small-scale irrigation schemes is necessary for increasing agricultural productivity and ensuring sustainable water resources management. This study assessed the hydraulic, agronomic, and structural performance of the Karfe Small-Scale Irrigation Scheme (65 ha), which diverts water from the Mojo River using a broad-crested weir and serves 162 households through right (2,250 m) and left (1,503 m) main canals. The evaluation was conducted during the main wheat cropping season (07 January–30 April 2026), considering spatial variability across head, middle, and tail sections of the command area. A mixed-methods approach was applied, combining field measurements, laboratory soil analysis, and farmer interviews. Soil were analysed for texture, bulk density, and soil moisture characteristics using standard laboratory equipment, while irrigation performance parameters were measured using bucket–stopwatch flow measurement techniques and canal observations. Performance indicators were computed based on FAO, IWMI, Bos et al. Khosla, and Terzaghi standards. The results show that the soils are dominantly clay (average 55.39%), with bulk density ranging from 1.10–1.13 g/cm³, field capacity of 0.37–0.41 m³/m³, and total available water of 130–170 mm/m. Application efficiency averaged 54.82% (moderate), while storage efficiency averaged 89.10%. Water supply indicators shown spatial imbalance, with SAR (1.08), RI (50% at tail), and DPR (0.58) confirming over-supply at the head and deficits at the tail. Conveyance efficiency averaged 76.09% (moderate), while distribution uniformity was 75%. Structural evaluation showed poor conditions with an average SCI of 2.36 and EI of 33.93%, indicating significant infrastructure deterioration. Major hydraulic failures were also observed, including misaligned weir (12.4° deviation), insufficient stilling basin length (2.19m deficit), floor length (1.55m) ,Froude number (3.93m) and FS Sliding(1.45),FS Overturning 1.88 the retaining wall instability under seismic loading and water Pressure. Based on these findings, mitigation measures including redesigned the retaining wall in two options (option1) is Masonry, option 2 reinforced concrete retaining wall) as alternative, canal rehabilitation, structural repair, improved irrigation scheduling, and strengthening of water user management are recommended to enhance overall system performance and sustainability.

Keywords: Small-scale irrigation, Water supply, Conveyance efficiency, Karfe, IWMI

Table of Contents

Addis Ababa University....................i
Declaration....................iii
Acknowledgment....................iv
Abstract....................v
List of Tables....................xi
List of Figures....................xiii
Abbreviation....................xiv
1. Introduction....................1
1.1 Background....................1
1.2 Problem Statement....................4
1.3 Objectives of the Study....................5
1.3.1 General Objective....................5
1.3.2 Specific Objectives....................5
1.4 Research Questions....................5
1.5 Significance of the Study....................5
1.6 Scope and Limitations....................6
1.7. Ethical Issues....................6
2. LITERATURE REVIEW....................7
2.1 Introduction....................7
2.2 Water resource and irrigation....................7
2.3 Irrigation Scheme....................8
2.3.1. Concept of Small-Scale Irrigation (SSI)....................9
2.3.2. Significance of Small-Scale Irrigation in Agricultural Development....................10
2.4 Evaluation Indicators for Irrigation System Performance....................10
2.4.1 Indicators of Water Supply Adequacy and Reliability....................10
2.4.2 Actual Discharge (Q)....................11

2.4.3 Net Water Supply (Q_{net}) 11
2.4.4 System Water Loss Percentage 11
2.4.5 Supply Adequacy Ratio (SAR) 12
2.4.7 Flow Variability, Reliability and Dependability indicators..12
2.4.2. Conveyance and Distribution Performance Indicators 12
2.5 Performance Evaluation of Small scale irrigation system 13
2.5.1 Concept of Performance Evaluation 13
2.5.2 Performance Evaluation of SSI 13
2.5.3. Purpose of Evaluating Performance of Small-Scale Irrigation (SSI) Schemes 13
2.6.1 Direct Flow Measurement Techniques 14
2.7 Types of Research data Sources 14
2.8 Crop Water Requirement and Irrigation Demand 14
2.8.1 Soil Characteristics and Water Availability 15
2.8.2 Soil Texture and Irrigation Efficiency 15
2.8.3 Irrigation Demand 15
2.8.4. CROPWAT 8.0 and Clime what 16
2. 9 Review of Performance Evaluation of Small –Scale Irrigation Studies 16
2.9.1 Global Development of Irrigation Performance Evaluation 16
2.9.2 Evaluation of Irrigation Performance in Africa 17
2.9.3 Evaluation of Irrigation Performance in Ethiopia 17
2.10 Key Challenges in Ethiopia SSI Schemes 18
2.10.1 Technical Challenges 18
2.10.2 Institutional Weaknesses 18
2.10.3. Socio-economic Barriers 18
2.11 Strategies for Enhancing the Performance of Small-Scale Irrigation 19
2.12 Research Gaps 19
2.13 Summary of the literature review 20
3. Research Methodology 20
3.1 Study Area 21

3.1.1. Location 21
3.1.2 Climate....23
3.1.3 Topography....26
3.1.4 Population 26
3.1.5 Soil type....26
3.1.6 Land use land cover....26
3.2 Materials used during the study....27
3.3 Methods Used....28
Procedure....29
Procedures 30
3.4 Data Analysis method....33
3.4.1 Analysis of Water Supply Adequacy 33
3.4.1.3 Estimation of Crop Water Requirement (CWR)....39
3.4.2 Performance Evaluation of the canal water delivery p system. 43
3.4.2.1 Performance Evaluation of the distribution system 43
3.4.6. Delivery Performance Ratio (DPR) 46
3.4.3 Evaluation of Irrigation Structure Performance....46
3.4.4 Farmers' Irrigation Scheduling and Water Management Practices 52
3.4.5 Formulating Mitigation Strategies 52
3.4.6 Sampling Methods....53
3.4.7 Overall the scheme performance....54
3.7 Conceptual framework 55
4. Result and Discussion 56
4.1 soil laboratory results and satirical analysis....56
4.1.1 Soil texture Characteristics 56
4.1.2 Bulk Density Determination....57
4.1.3 Combined Soil Water Characteristics, Soil Moisture and Water Availability 57
4.1.4 Application Efficiency (Ea) & Storage Efficiency (Es) 59
4.1.5 Storage Efficiency (Es)....59
4.2 Water Supply Adequacy and Reliability....60

4.2.1 Supply Adequacy Ratio (SAR) 60
4.2.2 The Readily Supply Ratio (RSR) 62
4.2.3 Reliability Index (RI) 63
4.2.4 Relative Water Supply (RWS) 63
4.3 Evaluation of the delivery Performance of the canal system..64
4.3.1 The conveyance efficiency 64
4.3.2 Conveyance losses (CL) 65
4.3.3 Distribution Uniformity (DU) 66
4.3.4. Equity Index (EI)...67
4.3.7 Overall Irrigation Efficiency 69
4.4. Evaluation of Irrigation scheme Structure Performance 70
4.4.1 Structural Condition Index (SCI) 70
4.4.2 Effectiveness of Infrastructure (EI) 72
4.4.3 Sedimentation Severity Index (SSI) 74
4.4.4 The Structural Deformation and Stability...76
4.5 Farmers' Irrigation Scheduling, Water Management and Institutional Performanc……………..84
4.5.1 Socio-Economic Characteristics of Respondents...84
4.5.2 Irrigation Scheduling 85
4.5.2.1 Decision-Making in Irrigation Scheduling 85
4.5.2.2 Irrigation Scheduling Practices 86
4.5.3 Water management Practices 87
4.5.3.1 Basis of Irrigation Timing Decision 87
4.5.3.5 Water Control and Infrastructure Use 89
4.5.4 Institutional Performance...89
4.5.4.1 Institutional Support and Capacity Building..89
4.5.4.6 Challenges in Irrigation Practices 91
4.5.5 The Irrigation Water Users Association (IWUA) 91
4.5.6 Major Observed results..92
4.5.7 Farmer Management Index (FMI) Evaluation...92
4.6. Overall scheme performance...93

4.7 Mitigation Strategies for Improving Irrigation System Performance 95
4.7.1 Water Supply Adequacy of the Irrigation Scheme 96
4.7.2 Performance of Canal Water Delivery system 96
4.7.3 Performance of the scheme Irrigation Structures 97
Table 4.59: Foundation and Construction Details 117
(1).Selected Suitable Crops for Karfe 121
(4).Water Management at the field 122
(5).Farmer Training and Extension Program..122
5. Conclusion and Recommendation 122
5.1: Conclusion 123
5.2 Recommendations 125
5.2.1Technical and Structural Recommendations 125
5.2.2 Water Management and Operational Recommendations 125
5.2.3 Institutional and Capacity Building Recommendations 125
5.2.4: Future Research Recommendations 125
6. Reference 126
7. Appendix 134
7.1Appendix A: Hydraulic...134
7.2 Appendix B: Climatic Data...136
7.3 Appendix Figure..137
7.3.1 Household Questionnaire for Irrigation Users 138

List of Tables

Table 2.1 Irrigation scheme classification based on area 9

Table 2.2 Irrigation scheme classification in Ethiopia 9

Table 3.1 Household Distribution by Community in Karfe Kebele 26

Table3.1: Materials used during the data collection and analysis. 27

Table 3.4: Acceptable Limits for Weir Axis Deviation Based on IS 6966:1973 50

Table 3.5: Design Criteria for Floor Length and Exit Gradient (Khosla et al., 1954) 51

Table 3.6: Accepted standards to design Stilling Basin Performance 51

Table3.7: Accepted standards of Stability Criteria Evaluation for Gravity Retaining Wall 52

Table 4.1: Soil textural class of the karfe scheme 56

Table 4.3: Combined Soil Water Characteristics of Karfe irrigation scheme 58

Table 4.4: Application Efficiency (Ea) & Storage Efficiency (Es) for Karfe SSI scheme 59

Table 4.5: Adequacy of water delivery performance of the Karfe SSI scheme 61

Table4.6: Readily Supply Ratio of the Karfe SSI Scheme 62

Table 4.7: Reliability index of the Karfe Irrigation Scheme 63

Table4.8: Relative Water Supply by Canal Section of the scheme 63

Table 4.9: Conveyance efficiency and Conveyance Loss of the Karfe SSI scheme 64

Table 4.10: Field Distribution Uniformity (DU) Based on Soil Moisture Measurements......66

Table 4.11: Variability and Uniformity of Water Distribution along scheme canal 68

Table 4.12 Monthly Delivery Performance Ratio at each section of the Scheme 68

Table 4.13: Structural Condition Index (SCI) Evaluation of Irrigation Scheme Components 71

Table 4.14: Infrastructure Effectiveness (EI) Across Irrigation System Components 73

Tabl.4.15: Analysis of the Sedimentation Severity Index for Irrigation Structures of the scheme 75

Table4.16: Weir Axis Alignment and Deviation Analysis Indicators 77

Table 4.17: Assessment of Floor Length Sufficiency and Exit Gradient......78

Table 4.18: Summary of Floor Length Adequacy and Exit Gradient Analysis result 79

Table 4.19: Step-by-Step Procedure for Hydraulic Jump and Stilling Basin Design validation......80

Table 4.20: Retaining Wall Stability Results – Critical Foundation Section 81

Table 4.21: Summary of All Retaining Wall Sections......82

Table 4.22: Compliance with Standard Limits (Lower Section, Saturated + Earthquake) 83

Table 4.23: Final Comparative Summary values of hydraulic and structure performance......83

Table 4.24: Socio-economic profile of irrigation users' in Karfe scheme 84

Table4.25 the irrigation scheduling practise in the scheme 85

Table 4.26: irrigation timing Scheduling method 86
Table 4.27: Awareness about the irrigation scheduling of farmers 86
Table 4.28: Irrigation Water Use Practices in the scheme 87
4.29: Irrigation duration in the scheme farmers practical 87
Table4.30: Irrigation method 88
Table 4.31: Types of Irrigation Technology Used by Farmer 88
Table 4.32: Use of water control structures 89
Table 4.33: Training and Institutional Support of the irrigation scheme 89
Table 4.34: Conflict Occurrence and Management in the Irrigation Scheme 90
Table4.35: Causes of conflict in the irrigation scheme 90
Table 4.36: Maintenance Responsibility in the scheme 91
Table 4.37: Challenges affecting the irrigation scheme 91
Table 4.138: IWUA Committee Members with Responsibilities in the scheme 92
Table 4.39: Assessment of the Farmer Management Index (FMI) in the scheme 93
Table 4.40: Integrated evaluated indicators to compute overall scheme performance 94
Table 4.41: Summary of Design Input Data and Assumptions 99
Table 4.42: summarized Vertical Forces and Moments 101
Table 4.42: Summary of Stability analysis 102
Table 4.43: Revised dimension values 102
Table 4.44: Vertical Forces and Moments using revised values 103
Table 4.45: Stability Results (Preliminary Check) 103
Table 4.46: Final Stability Summary 103
Table 4.47: Vertical Forces and Moments using the new revised values 104
Table 4.48: Stability Analysis Results for with-Drained and without drained Conditions 104
Table 4.50: Calculation of Loads and Bending Moment on Heel Slab of Retaining Wall 107
Table.4.51: Foundation and Construction Details of Masonry Retaining Wall 108
Table 4.52: Foundation Design Parameters and Construction Specifications 108
Table 4.53: Summarized final design dimension values 109
Table 4.54: Final Stability Check Results of Retaining Wall Design 109
Table 4.55: Detail work cost estimation of the masonry retaining wall 110
Table 4.56: Detailed Activities of the construction Work 111
Table 4.57: List of Design Input Data and Assumptions 112
Table 4.58: Vertical Loads and Stabilizing Moments 114

Table 4.59 :foundation safety and structural durability. 117
Table 4.60: Scour Protection Measures for Weir Deviation (12.4°)..117
Table 4.61: Summary of Final Design Dimensions...117
Table 8.62: Stability Analysis Summary...118
Table 4.63: Detailed Bill of Quantities and Cost Estimate for Reinforced Concrete Retaining wall ...118
Table 4.64: Construction Work Schedule for RC Retaining Wall 119
Table 4.65: Compering of the two options using best parameters...119
Table 4.66: using GPA method selecting surface irrigation method for karfe scheme 121

List of Figures

Figure 1: Study area map location. 22
Figure 2: Karfe SSI weir intake structure...24
Figure 3: Average monthly min, max temperature and relative humidity for the scheme 24
Figure 4: Average monthly wind speed for the scheme..24
Figure 5: Average monthly sunshine hour and solar radiation of the scheme 25
Figure 6: Average monthly rainfall, effective rain fall and R. ETo of the Scheme 25
Figure7: Conceptual framework 55
Figure 8: The Karfe weir site figure...78
Figure 9: Collapsed Retaining wall image 118
Figure 10: Designed concrete Reinforced retaining wall...120

Abbreviation

Abbreviation	Full Meaning	Purpose
AWC	Available Water Content	Water available for crop use
BD	Bulk Density	Soil compaction and infiltration
CGIAR	Consultative Group on International	Food security research
CTBE	College of Technology and Built Environment	Academic college affiliation
CWR	Crop Water Requirement	Amount of water needed by a crop
ETc	Crop Evapotranspiration	To irrigation water demand estimation
ETo	Reference Evapotranspiration	Atmospheric water demand for crops
FAO	Food and Agriculture Organization	Irrigation standards and guidelines
FS	Factor of Safety	Structural stability indicator
GPS	Global Positioning System	Field surveying and spatial data
ha	Hectare	Land area measurement
ILSSI	Initiative for Smallholder Sustainable Intensification	Is a global research partnership reduce poverty
IWMI	International Water Management Water Institute	Water resources research
Kc	Crop Coefficient	Crop water requirement adjustment
km	Kilometre	Distance measurement
km/hr	Kilometres per hour	Wind speed measurement
l/s	Litters per second	Flow discharge unit
m	Meter	SI unit of length
MC	Main Canal	Primary irrigation conveyance channel
mm	Millimetre	Soil and irrigation depth measurement
m^3/s	Cubic meters per second	Large-scale discharge unit
MOWE	Ministry of Water and Environment	National water resource authority
O&M	Operation and Maintenance	Operation and maintenance
OPI	Overall Performance Index	Overall irrigation system performance
PSI	Policy Studies Institute	Policy research institute
RAW	Readily Available Water	Easily accessible soil moisture for crops
SSI	Small-Scale Irrigation	Type of irrigation scheme studied
USBR	United States Bureau of Reclamation	A U.S.agency responsible for irrigation and water resources development.
WUA	Water Users Association	Local irrigation management organization

1. Introduction

1.1 Background

Water is a vital natural resource essential for human survival, ecosystem sustainability, and socio-economic development (IWMI, 1985). It serves as the most critical input in agriculture, which accounts for approximately 72% of global freshwater withdrawals, while agricultural water use represents nearly 90% of total consumptive use in many regions due to evapotranspiration and crop demand (UN-Water, 2025). Irrigation plays a major role in global food production, with irrigated agriculture covering about 20–30% of cultivated land but contributing nearly 40% of global crop production due to higher productivity and cropping intensity compared to rain-fed systems (FAO 2018; Goals, 2023). The distribution is not even, 68% in Asia, followed by the Americas (17%), Europe (9%), Africa (5%), and Oceania (1%). However Despite its importance, water scarcity is a growing global challenge. Around 2.2 billion people lack access to safely managed drinking water, while billions more experience water stress driven by population growth, climate change, pollution, and increasing demand (FAO, 2018; Goals, 2023; UN-Water, 2025). Small-Scale Irrigation (SSI) systems are increasingly recognized as important tools for improving water security, agricultural productivity, and resilience to climate variability, drought, and rainfall inconsistency (FAO, 2018; IWMI, 2010). However, many SSI schemes operate below their design capacity due to technical, environmental, institutional, and socio-economic constraints(Bos et al., 2005). These challenges include poor design and construction, sedimentation, seepage losses, canal erosion, weak maintenance, inadequate funding, weak Water User Associations (WUAs), illegal water abstraction, and inequitable water distribution. To address these challenges, performance evaluation of irrigation schemes has become essential. Such assessments help identify inefficiencies in water delivery, distribution, and utilization, and measure key indicators such as conveyance efficiency, application efficiency, reliability, and equity(Bos et al., 2005b; Clemmens & Molden, 2007). Performance evaluation also supports improved water management, better decision-making, and enhanced sustainability of irrigation systems(Bos et al., 2005b; IWMI, 2024).

In Ethiopia the backbone of country economy is Agriculture empowering of more than 70% population and play basic role in national food security, using rain–fed, but this is not sufficient to satisfy the food security of the whole population. The nation is estimated to have 122 billion m³ of renewable surface water, between 25 and 40 billion m³ of groundwater, and approximately 5.8 million hectares of land suitable for irrigation; however, the utilization of these resources remains limited, especially in small-scale irrigation schemes, due to poor infrastructure, weak institutions, and inadequate water management. As a result, agriculture largely depends on rainfall, underscoring the need for improved management and performance evaluation of irrigation systems (MOWIE, 2022). commonly Ethiopia SSI schemes are river diversion, surface irrigation systems ,shallow wells, motor, solar pumps and Spate irrigation schemes (MOA, 2024).The main objective includes: ensuring food security (IWMI, 2024). But most Ethiopian SSI schemes are underperformance due to weak institutional management, poor operation and maintenance, improper water management practices, technical and design problems (Asefa et al., 2023; Awulachew & Ayana, 2011). Therefore the assessment of irrigation schemes is required. to improve the overall productivity and sustainability of irrigation schemes (Girma et al., 2020; Haileslassie et al., 2020).

The Karfe Small-Scale Irrigation Scheme, located in Adaa Chukala Woreda of East Shoa Zone, Oromia, is approximately 22 km from Bishoftu. It irrigates about 65 hectares and benefits around 162 smallholder farmers cultivating crops such as potatoes, tomatoes, onions, cabbage, and lettuce. The scheme diverts water from the Mojo River, a tributary of the Upper Awash Basin. Despite its importance in supporting local livelihoods and food security, the scheme faces multiple challenges. These include deterioration of hydraulic structures, seepage from unlined canals, sediment accumulation, non-functional gates, lack of flow measurement structures, and inadequate irrigation scheduling. Operational inefficiencies have led to over-irrigation in upstream areas and water shortages downstream. Institutional problems such as weak Water User Associations, unauthorized water abstraction, poor maintenance, and insufficient farmer awareness further aggravate system inefficiencies. Consequently, these issues have reduced conveyance efficiency, water distribution equity, and overall system performance (MoWE, 2023).

Several studies in Ethiopia show that small-scale irrigation (SSI) systems significantly improve household income, agricultural productivity, and food security, especially in drought-prone regions such as Oromia, Amhara, and Tigray (Deressa et al., 2009; FAO (2018), 2018). However, their performance is often limited by technical, institutional, and environmental challenges, including poor water management, sedimentation, illegal water abstraction, weak maintenance, and inequitable water distribution (Asefa et al., 2023; Mekonnen & Gerber, 2017; Tangban & Oku, 2020). Institutional weaknesses such as limited farmer participation and weak Water Users Associations further reduce system efficiency, while environmental factors like drought and rainfall variability affect reliability (Tadesse, 2017; Wanaet al., 2025). Although SSI schemes improve livelihoods, many operate below capacity due to poor coordination between water supply and demand. Adequate maintenance and improved management are essential for enhancing SSI performance. However, irrigation systems commonly face inequitable water distribution, weak institutions, poor maintenance, and environmental stresses such as drought and rainfall variability(Alebachew et al., 2018; Asefa & Tadesse, 2023). Previous studies around Karfe mainly focused on socio-economic benefits, with limited attention to technical and operational performance. Most research is also comparative rather than case-specific. Therefore, a detailed, scheme-level evaluation is needed to identify constraints and improve the sustainability of the Karfe SSI Scheme.

Therefore, this study assessed the performance of the Karfe Small-Scale Irrigation Scheme using field measurements, stakeholder surveys, and analytical tools. It evaluated water supply–demand balance, conveyance and distribution efficiency, hydraulic condition, and farmers' water management practices using key indicators such as adequacy (Ea), reliability (ER), equity (E), dependability (DR), seasonal adequacy ratio (SAR), and application efficiency (Ec). Data were collected from field observations, soil laboratory analysis, questionnaires, KIIs, FGDs, and secondary sources, and were analyzed using Microsoft Excel, ArcGIS, and CROPWAT 8.0. The study identified major technical, operational, and institutional constraints and proposed evidence-based solutions to improve irrigation efficiency and ensure the long-term sustainability of the scheme.

1.2 Problem Statement

Small-scale irrigation (SSI) schemes play a vital role in improving agricultural productivity, food security, and farmers' livelihoods. However, many schemes operate below their potential due to inequitable water distribution, high water losses, deteriorated infrastructure, and weak management practices(Asefa et al., 2023). Therefore, performance evaluation is essential to identify constraints and improve the efficiency, reliability, and sustainability of irrigation systems e(IWMI, 2020; Molden et al., 1990).

Despite their importance, many small-scale irrigation schemes in Ethiopia perform below their potential due to sedimentation, infrastructure deterioration, inefficient water management, inequitable distribution, and weak institutional support, resulting in low water use efficiency and reduced system sustainability (Asefa & Tadesse, 2023; Awulachew & Ayana, 2011a)

The Karfe Small-Scale Irrigation (SSI) Scheme was developed to improve agricultural productivity through equitable and efficient utilization of water diverted from the Mojo River. However, the scheme has been affected by technical, hydraulic, operational, and institutional challenges, including sedimentation, canal deterioration, non-functional control structures, inequitable water distribution, illegal water abstraction, weak Water Users Association performance, and poor on-farm water management practices. These constraints have reduced water use efficiency, system reliability, and agricultural productivity. Since no comprehensive performance evaluation had previously been conducted, this study assessed the technical, hydraulic, and institutional performance of the scheme to identify key constraints and provide recommendations for improving irrigation efficiency, sustainability, and farmer livelihoods.

1.3 Objectives of the Study

1.3.1 General Objective

The general objective of this study is to evaluate the performance of the Karfe Small-Scale Irrigation Scheme in terms of water use efficiency, canal and structure performance, and management practices, and to propose strategies for improving irrigation efficiency and sustainability.

1.3.2 Specific Objectives

1. To examine the adequacy of water supply to the irrigation scheme.
2. To evaluate the water delivery performance of the canal system.
3. To assess the overall performance of irrigation structures.
4. To analyse farmers' water management practices.
5. To propose mitigation strategies for improving irrigation performance.

1.4 Research Questions

1. Is the water supply to the Karfe Irrigation Scheme adequate?
2. What is the water delivery performance of the canal system?
3. What is the overall performance of irrigation structures?
4. What strategies can improve irrigation performance in the scheme?

1.5 Significance of the Study

- ❖ To identify critical gaps affecting irrigation performance and propose measures to ensure the long-term sustainability of the scheme.
- ❖ To improve water-use efficiency by reducing conveyance, distribution, and on-farm water losses.
- ❖ To enhance agricultural productivity through reliable & efficient irrigation water delivery.
- ❖ To provide practical, site-specific recommendations to woreda and zonal offices for improved planning, operation, and maintenance of small-scale irrigation schemes.
- ❖ To generate evidence-based recommendations to support policies, technical guidelines, and investment decisions of the Ministry of Agriculture and related institutions.
- ❖ To strengthen the capacity of irrigation managers and local authorities through clear performance indicators and actionable management insights.
- ❖ To promote sustainable and climate-resilient water resources management
- ❖ To fill existing knowledge gaps on small-scale irrigation performance in rural Ethiopia using empirical evidence and to serve as a baseline for future research, monitoring, and development interventions in irrigation performance and sustainable agriculture.

1.6 Scope and Limitations

Scope: the study was focused on evaluating the performance of the Karfe Small-Scale Irrigation (SSI) Scheme from The head to tail end, with emphasis on water supply adequacy, canal conveyance and distribution efficiency, the condition of irrigation structures, and farmers' water management practices and proposed mitigation measures by giving priority for focused areas. The research was involved systematic field measurements, direct observations, structured questionnaires, interviews, and surveys conducted throughout the scheme's command area, extending from the head works to downstream outlets. The analysis was confined to technical, operational, structural, and managerial aspects of irrigation performance. The results are assessed against the original document, weir design standards, FAO & IWMI guidelines and principles, and relevant literatures and practical mitigation strategies are proposed to enhance the overall efficiency, reliability, sustainability of the Karfe SSI scheme. However, the study does not address the environmental or socio-economic impacts of the scheme and focuses exclusively on major crops within the command area.

Limitation: No historical flow data was available for comparison with current conditions. Therefore, flow measurements were mainly carried out using the bucket–stopwatch method due to the absence of flumes and automatic sensors. Although a 90° V-notch weir had been designed for the main canals, it could not be permanently installed because farmers opposed closing the canal during the critical irrigation season (January–March), when continuous 24-hour irrigation was practiced. As a result, alternative methods such as the volumetric bucket–stopwatch approach for off-takes and the area–velocity method for main canals were used, with repeated measurements taken and averaged to improve accuracy.

1.7. Ethical Issues

Ethical considerations are essential for ensuring research integrity and protecting participants Resnik et al.(2015), e note that adherence to ethical standards improves the credibility and reliability of scientific research. Accordingly, this thesis maintained academic integrity by properly citing all sources and strictly avoiding plagiarism, fabrication, or falsification of data (MoE, 2018). Participant confidentiality was ensured by anonym zing personal information of farmers and irrigation officials, and informed consent was obtained prior to data collection in line with ethical protocols (Israel, 2015).The study also complied with Ethiopian laws, regulations, and local cultural values. Overall, these measures ensured that the research was credible, ethical, and socially responsible.

2. LITERATURE REVIEW

2.1 Introduction

Literature review is finding ,discussing and analyse zing of information from published academic Books, Journal articles ,reports ,policy documents and Web based sources that directly related in a particular title in order to gain a detail understanding of the previous studies findings, methodologies, limitations , knowing standards, formulas, identify gaps and put theoretical and empirical rules for new studies (Hart,1998;Bootet al.,2005). Based on this concept this literature review discusses ,searching and surveying of theoretical backgrounds ,empirical researches, key performance indicators, basic standards, polices , guideline rules, farmer management practices ,limitations and methods ,gaps, conceptual frame works information's using necessary published data sources ,directly approaches to the Performance evaluation of Karfe Small scale irrigation scheme .

This literature review examined studies from international, African, and Ethiopian to analysis their objectives, methodologies, solutions, recommendations, limitations/weakness and gaps to peak out researchable ideas for this research and to recommend for the future researcher. The review indicates problems such as conflicts, water losses, poorly maintained system structures, poor water management, weak coordination of institutions and water-user associations (WUA).According to FAO (2018) Small scale irrigation schemes (SSI) are mandatory to increase agricultural productivity, protection of food security, support rural households' income basically where unreliable rain fall and variable climate condition .They designed to supply water for agricultural crop production, by conveyance efficient water, equitable distribution, and proper for management (Molden et al.,1990). At the last point of this review indicates study gaps to be studied by this research using the compressive performance evaluation methods of the SSI of Karfe in site specific operational, technical, institutional and infrastructural conditions using design, management and field variable measurements to obtained best strategy and recommendation of the research to improve performance of the scheme.

2.2 Water resource and irrigation

Water resources are characterized as the accessible and manageable quantities of water sourced from surface water, groundwater, and collected rainfall for irrigation, especially during arid periods to facilitate crop growth and yield (FAO, 2012). As reported on FAO (2018) agriculture is responsible for approximately 70% of global freshwater withdrawals, with irrigation constituting the predominant portion. According to IWMI (2024) the pressures on water resources have escalated due to population growth, urbanization, and developing food demands. Irrigation is recognized as a crucial factor in stabilizing agricultural output, as noted by (Bos et all.,1994) and (FAO, 1996);however, the effectiveness of irrigation systems can differ significantly due to variations in infrastructure, management practices, and institutional capabilities. Global assessments of small-scale irrigation systems utilize performance indicators such as conveyance efficiency (Ec), distribution efficiency (Ed), application efficiency (Ea), water supply adequacy (PA), and reliability (PR) to measure effective performance (FAO ,1996) and (Molden et al.s,1990).

As stated by IWMI (2024) and FAO (2020) about the Small-scale irrigation (SSI) in Africa, even if SSI plays a key role in improving agricultural productivity and rural livelihoods in areas with unreliable rainfall. It has been shown to increase crop yield, income, and food security. However, many schemes perform below their potential due to challenges such as water losses, sedimentation, poor maintenance, and weak management systems. Based on Awulachew et al.(2011) and) MOWE(2019) reported that, Ethiopia have abundant water resources and high irrigation potential, only a small portion has been developed, mainly through SSI, with relatively low efficiency. Ethiopia's limited utilization of irrigation potential is mainly due to inadequate infrastructure and poor water management, institutional and financial constraints, and weak governance and technical support, as well as the absence of systematic performance monitoring, which results in low efficiency, inequity, and high water losses.

This limitation reduces the capacity of decision-makers to undertake timely rehabilitation and management interventions, thereby increasing the likelihood of system deterioration and failure. Moreover, it constrains

2.3 Irrigation Scheme

According to the MoWE(2019) and FAO (1997) irrigation has been acknowledged for a long time as a crucial intervention to improve agricultural productivity in areas where rainfall is insufficient, inconsistent, or unevenly distributed. In this regard, the notion of an irrigation scheme has been extensively defined and examined in the literature pertaining to irrigation engineering and water management. As stated by FAO (1997) An irrigation scheme is a designed hydraulic system that diverts water from natural or artificial sources, conveys it through canals or pipes, and distributes it to fields in a controlled manner to meet crop water requirements. It emphasizes key components such as diversion, conveyance, distribution, and application in irrigation development. As Awulachew et al.(2011), Irrigation development costs vary with scheme size, with large-scale schemes (>10,000 ha) requiring the highest investment (about 16,000 USD/ha), while small-scale schemes (<2,000 ha) are less costly (around 4,000 USD/ha). This difference reflects variations in infrastructure, technology, and management requiremnts.

Table 2.1 Irrigation scheme classification based on area

No	Irrigation scale	Command area (ha)	Potential Area (Million ha)	Average cost	Range cost
1	Large	>10,000	1.9	16,000	5,000-50,000
2	Medium	2,000-10,000	0.27	9,000	4,000-15,000
3	Small	<2,000	2.2	4,000	1,000-6,500

According to the Awulachew et al. (2007) irrigation systems in Ethiopia is categorized as small-scale (<200 ha), medium-scale (200–3,000 ha), and large-scale (>3,000 ha) irrigation systems and the investigation of his study result , suggests that the total potential area suitable for irrigation in Ethiopia is approximately 4.3 million hectares, with small-scale systems accounting for nearly 50% of the national potential, primarily influenced by river basin characteristics and the availability of land and water resources.

Table 2.2 Irrigation scheme classification in Ethiopia

No	Irrigation scale	Command area (ha)	Potential Area (Million ha)
1	Large	> 3,000	1.9
2	Medium	200–3,000	0.27
3	Small	< 200	2.2

2.3.1. Concept of Small-Scale Irrigation (SSI)

Based on Kassa et al. (2010) Small-scale irrigation (SSI) in Ethiopia is a farmer-managed system (<200 ha) supported by government/NGOs, using simple infrastructure like weirs and canals to improve dry-season water access, boost productivity, and ensure equitable water distribution. As noted by FAO (2012), SSI schemes frequently depend on river diversions, small ponds, or groundwater, and are governed through community-based frameworks to enhance household food security and income. This characterization is consistent with FAO standards, which define SSI as systems driven by smallholders that utilize simple and cost-effective technologies, including treadle pumps, drip irrigation, or small motorized pumps (IWMI, 1985). SSI is especially advantageous for smallholder farmers who possess moderate water and land resources, have limited investment capabilities, and require prompt enhancements in household food security (Bekele, 2021).

2.3.2. Significance of Small-Scale Irrigation in Agricultural Development

As stated on IWMI (2015) Small-scale irrigation (SSI) is a cost-effective and climate-resilient system that improves agricultural productivity through dry-season and multiple cropping, stabilizes yields, enhances food security, supports crop diversification and income generation, and empowers rural communities. However, its performance is often limited by poor maintenance, water losses, and weak management, requiring systematic evaluation to improve efficiency and sustainability (Barbio et al., 2022).

2.4 Evaluation Indicators for Irrigation System Performance

Evaluating performance is a fundamental component in the examination and improvement of irrigation systems, as it provides a structured approach for measuring the effectiveness of water resource management and usage. As highlighted by Molden et al.(1990) and along with insights from the FAO, (1996), performance metrics are essential tools for pinpointing the strengths and weaknesses of these systems. These metrics assess irrigation systems quantitatively and qualitatively across hydraulic, operational, structural, and institutional aspects. Hydraulic metrics focus on the efficiency of water delivery and distribution, while operational and management metrics emphasize scheduling, equity, and institutional effectiveness. However, several researchers argue that depend on completely on one category of metrics may result in an incomplete perspective. For instance,(D. Molden, 1997) principles, indicates the significance of system-level performance, whereas (FAO, 1992) frameworks emphasize field-level relevance and outcomes for farmers. This highlights the need for integrated assessment combining technical efficiency and user-focused performance. In small-scale irrigation systems, especially in developing countries, performance evaluation is critical due to resource, infrastructure, and management constraints, with poor performance often leading to inadequate water delivery, unequal distribution, and weak institutional framework (FAO, 1992). Therefore, a comprehensive set of metrics is necessary for a thorough evaluation of irrigation systems. Based on this, the study uses specific indicators utilized to evaluate the effectiveness of the chosen irrigation system, focusing in all scheme systems manner.

2.4.1 Indicators of Water Supply Adequacy and Reliability

The adequacy and reliability of water supply are widely acknowledged as the most essential indicators of the performance of irrigation systems. As noted by Bos et al., (2005) and Molden et al., (1990), adequacy pertains to the degree to which the water provided satisfies the water needs of crops, while reliability pertains to the consistency and predictability of water delivery over time. While these concepts are generally accepted, various authors interpret them from slightly different angles. For instance, Clemmens et al., (2007) measure reliability through supply ratios, concentrating on temporal consistency. Irrigation performance assessment considers both temporal reliability (timely water delivery) and spatial equity (fair water distribution), which are particularly important in small-scale irrigation systems where head–tail disparities are common.

Research conducted within the frameworks established by(FAO, 2012) indicates that inadequate and unreliable water supply frequently results in yield variability, diminished water productivity, and dissatisfaction among farmers. These issues are more severe in systems with weak control structures and poor management. Although adequacy and reliability indicators are commonly used, they often ignore site-specific conditions. Therefore, this study applies these indicators in a local context for a more realistic performance assessment.

2.4.2 Actual Discharge (Q)

Actual discharge serves as a fundamental hydraulic parameter for assessing the performance of irrigation systems. It denotes the instantaneous flow of water at a designated point within the system, measured under actual field conditions. As noted by FAO (1996) and Bos et al. (2005),actual discharge offers a direct measure of the volume of water being supplied in relation to the system's design capacity. The assessment of discharge in field conditions is generally based on the principle of continuity: $Q = A \times Vav$ Where: Q is discharge (m^3/s), A is cross-sectional area of flow (m^2) and Vav is average velocity (m/s).

2.4.3 Net Water Supply (Q_{net})

Net water supply refers to the effective volume of water available for crop use after deducting all conveyance and operational losses such as seepage, evaporation, leakage, and spills (FAO, 1992). t is derived from the water balance principle, expressed as $Q_{net} = Q_{in} - Q_{out}$ (FAO, 2002). In irrigation studies, this concept is closely linked to system performance and efficiency, as losses directly reduce the water reaching the crop root zone. Studies such as (Molden et al.(1990) and FAO irrigation performance frameworks highlight that improvements in conveyance and application efficiency increase net water supply and overall water productivity. Therefore, net water supply is a key indicator for evaluating irrigation system effectiveness and management performance.

2.4.4 System Water Loss Percentage

As noted on(Bos et al., 2005),the water loss in irrigation systems refers to the amount of water that does not arrive at the designated fields, which can occur due to seepage, evaporation, leakage, or operational spills, frequently resulting from inadequate management practices. Furthermore, the FAO (2012) emphasizes that precise estimation of these losses is essential for evaluating irrigation efficiency, enhancing water management, and optimizing net water supply. This issue is particularly critical in small-scale irrigation (SSI) systems, where even slight losses can significantly diminish water availability and restrict crop productivity.

2.4.5 Supply Adequacy Ratio (SAR)

The Supply Adequacy Ratio (SAR) evaluates the extent to which the available water satisfies the water needs of crops. As noted by FAO (2012), SAR is commonly employed in small-scale irrigation to evaluate system efficiency, facilitate crop planning, and manage scarce water resources. The calculation of SAR is based on the ratio of net water supply (Qnet) to the crop water requirement (Qcrop).

2.4.6 Mean Daily Flow (MDF)

Hydrological flow concepts are essential for water resources assessment. As stated by WMO (2009), Mean daily flow (MDF) is the average 24-hour discharge, design discharge is the planned capacity used in hydraulic design, and actual discharge is the observed field flow, which may vary due to losses and operational conditions.Net water supply denotes the effective water available for crop use after accounting for losses such as seepage, evaporation, leakage, and operational spills, and is commonly expressed using the water balance relationship ($Q_{net} = Q_{in} - Q_{out}$) (Yusuf Beker, 2019). These losses significantly influence irrigation efficiency, as highlighted by (Clemmens & Molden, 2007),particularly in small-scale irrigation systems where infrastructure and management constraints are prevalent. This indicates that during the performance evaluation of SSI in order to compute the amount of water actually applied in the field to know the exact satisfaction of crops water requirement based on this way the karfe study was evaluated its adequacy performance of the scheme.

2.4.7 Flow Variability, Reliability and Dependability indicators

Flow variability and water supply reliability are key indicators in evaluating irrigation system performance (IWMI, 2007). Flow variability is commonly measured using the coefficient of variation (CV), which expresses the ratio of standard deviation to mean flow, with higher values indicating greater discharge fluctuation and reduced reliability (Bos et al.,2005). Reliability Index ® reflects the probability that water supply meets crop water requirements without shortage, indicating the consistency of system performance (Haileslassie, 2016). Dependability Ratio (DR) measures the proportion of time that water supply is adequate relative to total demand periods, showing the frequency of satisfactory water delivery in systems.

2.4.8. Conveyance and Distribution Performance Indicators

Conveyance and distribution efficiency assess the effectiveness of water movement through canals and its allocation among users (FAO,1996). Conveyance efficiency evaluates the percentage of water delivered from the intake to downstream sections, while equity is assessed by comparing flows at the head, middle, and tail reaches of the canal (Bos et al.,2005).. In the context of SSI, an uneven distribution can reduce the performance and potentially lead to conflicts; therefore, it is essential to evaluate both efficiency and equity in the karfe irrigation scheme using the measured flow monthly average data (Molden et al., 2007).Irrigation performance is assessed using efficiency, equity, adequacy, and structural condition indicators to evaluate overall system performance and sustainability.

2.5 Performance Evaluation of Small scale irrigation system

2.5.1 Concept of Performance Evaluation

Performance evaluation is a structured approach for assessing the effectiveness of a system in meeting its goals(Armstrong, 2009). In the context of irrigation, it entails the measurement and analysis of water distribution and usage to evaluate the system's efficiency, equity, and reliability, all while promoting sustainable water management. This evaluation process aids in identifying strengths and weaknesses, reducing losses, enhancing operations, and equipping decision-makers with essential data for infrastructure maintenance and management strategies (FAO, 1996).

2.5.2 Performance Evaluation of SSI

According to Bos et al.(2005) and FAO (1996;2012), the evaluation of SSI performance involves a systematic assessment of water delivery, crop productivity, and management effectiveness. The Current methodologies integrate technical, operational, and socio-institutional indicators, emphasizing water adequacy, efficiency, reliability, equity, and the condition of infrastructure. In the case of Karfe SSI, the primary dimensions for evaluation include water supply, hydraulic efficiency, infrastructure status, and the management practices of farmers.

2.5.3. Purpose of Evaluating Performance of Small-Scale Irrigation (SSI) Schemes

According to the Molden et al.(1997) and (IWMI, 2024), Small-Scale Irrigation (SSI) performance assessment identifies system strengths and weaknesses by evaluating water adequacy, efficiency, equity, infrastructure condition, and institutional management to improve productivity, sustainability, and equitable water distribution.

2.6 Techniques and Methods for Measuring Water Flow in SSI

According to the FAO (1996) and Molden et al. (1990), accurate measurement of water flow is crucial for assessing the effectiveness of Small-Scale Irrigation (SSI) systems, such as the Karfe SSI (65 ha). Precise flow data facilitate the evaluation of water distribution, system efficiency, and crop water application. Flow measurement techniques are generally divided into direct and indirect methods, each possessing its own set of advantages and limitations that depend on factors such as canal characteristics, discharge, and available resources. Furthermore, these measurements are vital for determining key performance indicators, including conveyance efficiency.

2.6.1 Direct Flow Measurement Techniques

Direct flow measurement technique means taking information practically on the field using the Measuring materials. Precise measurement of water flow is crucial for assessing the performance of small scale irrigation (FAO, 1996). Direct techniques, such as V-notch weirs, are favoured due to their dependability and accuracy in low flow conditions, whereas indirect techniques like the float method are employed in situations where permanent structures are not feasible (IWMI, 2007; Pereira et al., 2009). Conducting measurements at critical points main intake, secondary outlets, and fields during various irrigation events facilitates the evaluation of conveyance, distribution, and application efficiency, thereby aiding in informed management and promoting sustainable operations.

2.7 Types of Research data Sources

Research data sources serve as the foundational elements of information utilized for analysis and decision-making, with their reliability having a direct impact on the credibility of studies (Kothari, 2004). Primary data is gathered directly by researchers through methods such as surveys, questionnaires, interviews, observations, and experiments, yielding information that is specific to the site and relevant to the context (Ishtiaq, 2019)). In the context of irrigation studies, this encompasses measurements of water flow, canal losses, crop water application, and farming practices, which are essential for calculating performance indicators like conveyance, distribution, and application efficiency (FAO, 1996). Secondary data consists of academic publications, government reports, and institutional databases, providing comparative and trend-related information (Kothari, 2004). The integration of both primary and secondary sources improves accuracy, minimizes bias, and facilitates a thorough assessment of irrigation performance (Ishtiaq, 2019).

2.8 Crop Water Requirement and Irrigation Demand

The assessment of crop water requirements (CWR) is crucial for the efficient management of irrigation systems. Research highlights that the precise evaluation of crop evapotranspiration, soil moisture availability, and irrigation scheduling is vital to guarantee the adequacy, reliability, and efficiency of water delivery, especially in small-scale irrigation (SSI) systems (Allen, 2000; FAO, 1996). The synchronization between water supply and crop demand is essential for maximizing water utilization and sustaining crop productivity.

2.8.1 Soil Characteristics and Water Availability

Soil characteristics play a significant role in determining irrigation efficiency and the ability to fulfil CWR. Physical factors such as texture, structure, bulk density, porosity, and hydraulic conductivity govern water retention, infiltration, and storage within the crop root zone (Allen et al., 1998). These attributes directly influence the total available water (TAW) and permissible depletion levels, which are critical for planning irrigation and assessing water adequacy: $TAW = (FC - PWP) \times Zr$,Where FC represents field capacity, PWP denotes permanent wilting point, and Zr signifies root depth(Allen et al., 1998b). Grasping these parameters allows for accurate computation of the water available to crops and facilitates effective irrigation management.

2.8.2 Soil Texture and Irrigation Efficiency

Soil texture, determined by sand, silt, and clay proportions, influences infiltration, drainage, and water-holding capacity. Sandy soils drain quickly with low retention, while clay soils retain more water but reduce infiltration and increase runoff (Pereira et al., 1998). As a result, soil texture affects irrigation frequency, water application efficiency, and the capacity to meet CWR. Methods for evaluating texture include field-based techniques, such as hand texturing, and laboratory analyses.

2.8.3 Irrigation Demand

According to the FAO (1998) and Doorenbos et al.(1977), irrigation demand is defined as the quantity of water necessary to satisfy crop water requirements when precipitation is inadequate, thereby promoting optimal crop development. This demand is a crucial element in the planning and management of irrigation systems, especially within small-scale irrigation (SSI) initiatives.

2.8.3.1 Crop Water Requirement (ETc)

As stated by Allen (2000), the crop water requirement signifies the amount of water essential to offset evapotranspiration, which encompasses both soil evaporation and crop transpiration. According to the FAO (1998), Crop Water Requirement (CWR) refers to the total volume of water necessary for a crop to satisfy its evapotranspiration demands under ideal conditions. This figure denotes the theoretical water requirement, presuming there are no constraints on water supply.

The calculation of crop water requirement can be expressed through the following equation:

$$ETc = Kc \times ETo$$

Where ETc denotes crop evapotranspiration, ET_o represents reference evapotranspiration determined by climatic factors, and Kc is the crop coefficient, which varies according to the type of crop and its growth phase.

2.8.4. CROPWAT 8.0 and Clime what

2.8.4.1 CROPWHAT 8.0

According to the FAO (2009), CROPWAT 8.0 is a decision-support tool designed to compute reference evapotranspiration, crop water needs, and irrigation scheduling. This software adheres to the guidelines outlined in FAO Irrigation and Drainage for effective irrigation planning. As stated by FAO (2009), CROPWAT necessitates climatic, crop, and soil information to accurately assess irrigation requirements.

2.8.4.2 CLIMWAT

According to the FAO (2009), CLIMWAT is a climatic database intended for use with CROPWAT. It offers extensive long-term monthly climate data, which includes: Minimum and maximum temperature Relative humidity Wind speed Sunshine hours Rainfall CLIMWAT provides dependable data for calculating reference evapotranspiration (ET_0), particularly in situations where local meteorological data is not accessible.

2.8.4.3 Main Calculations and Formulas Employed in CROPWAT

According to (Allen et al., 1998), the CROPWAT model utilizes the FAO Penman–Monteith method for calculating reference evapotranspiration (ET_0), incorporating essential climatic factors such as solar radiation, temperature, humidity, and wind speed. This approach is widely acknowledged as the benchmark for assessing atmospheric water demand in irrigation research (Pereira et al.(1998). Crop evapotranspiration (ETc) is derived from ET_0 and Kc, while irrigation requirements consider rainfall and efficiency losses. Soil-water parameters (AWC, TAW, RAW) guide irrigation scheduling. These form the basis of the CROPWAT model for irrigation planning.

2. 9 Review of Performance Evaluation of Small –Scale Irrigation Studies

2.9.1 Global Development of Irrigation Performance Evaluation

As stated by Molden et al.(1990), assessment of irrigation performance became a recognized field of study in the late 1980s and represented a transition from design-oriented assumptions to evaluations based on actual field conditions, introducing essential metrics such as adequacy, efficiency, equity, and reliability. They emphasized that failures in irrigation systems are often due to inadequate management and unequal distribution rather than a lack of water resources. In this context, Bos et al.(1994), created standardized evaluation frameworks that included hydraulic, agricultural, and management indicators, such as conveyance, distribution, and application efficiencies, which gained widespread acceptance in the assessment of small-scale irrigation (SSI) performance.

Likewise, the FAO (1996), reporting that the conveyance efficiency of unlined canals generally falls between 50% and 70%. They identified frequent water shortages at the tail-end of systems as a result of unequal distribution and insufficient maintenance, which compromise system reliability. A significant development was made by FAO (1998) with the introduction of the FAO Penman–Monteith method for estimating crop water needs, which facilitated effective comparisons between water supply and crop demand for performance evaluation. More recently, (IWMI, 2024), indicates that the necessity of integrating institutional factors with hydraulic indicators in assessing irrigation performance, pointing out that ineffective management systems and discrepancies between water supply and crop needs are major causes to low productivity and inefficiency.

2.9.2 Evaluation of Irrigation Performance in Africa

According to the Awulachew (2010), report about the assessment of irrigation performance in Africa was gained significant importance in the early 2000s, following the spread of Small-Scale Irrigation (SSI) initiatives aimed at enhancing food security and controlling poverty and numerous SSI projects throughout African nations, including Ethiopia, function below their intended capacity due to substantial conveyance losses, insufficient maintenance, and ineffective water distribution systems. The research underscored that the simple establishment of irrigation infrastructure does not ensure efficient system performance without appropriate management. Similarly, IWMI) (2015), indicated that conveyance losses in Sub-Saharan Africa frequently surpass 30–40%, which significantly diminishes water availability at the field level. The report also pointed out severe disparities in water distribution, where upstream users receive a greater share of water compared to downstream users, primarily due to inadequate institutional frameworks such as ineffective Water Users Associations (WUAs).

In a later study, (Bos et al., 2005), reported that small-scale irrigation schemes often experience unequal water distribution, poor maintenance, and weak management, reducing irrigation performance. The study emphasized that regular performance evaluation is essential to improve efficiency and sustainability.

2.9.3 Evaluation of Irrigation Performance in Ethiopia

The assessment of irrigation performance in Ethiopia has gained significant importance due to the persistent challenges posed by droughts and variability in rainfall, which hinder agricultural productivity. National assessments conducted by (Awulachew, 2010), indicated that small-scale irrigation (SSI) systems frequently function below their intended capacity, with conveyance efficiencies between 45% and 65%. Key factors that restrict performance include sedimentation, insufficient maintenance, and ineffective water distribution management, leading to considerable water stress for farms located at the tail-end. Moreover, institutional elements play a crucial role in determining irrigation effectiveness. The knowledge and practices of farmers also pose further limitations; a lack of understanding regarding irrigation scheduling and application depth contributes to diminished application efficiency (Tesfaye et al., 2020). In spite of these findings, the majority of research has concentrated on singular indicators, such as conveyance efficiency, without incorporating hydraulic efficiency, supply-demand equilibrium, infrastructure conditions, and institutional performance. This piecemeal approach restricts a holistic understanding of system functionality.

Consequently, contemporary research underscores the necessity for a comprehensive performance evaluation framework that integrates hydraulic,, structural, and institutional assessments to facilitate effective management and promote sustainable operations of SSI (FAO, 1996).

2.10 Key Challenges in Ethiopia SSI Schemes

Small-scale irrigation (SSI) initiatives in Ethiopia are acknowledged as crucial for enhancing agricultural productivity and improving rural livelihoods. Existing research indicates that their effectiveness is hindered by a variety of technical, institutional, socioeconomic, and regional factors.

2.10.1 Technical Challenges

As emphasized by Girma (2007) and Gebremedhin et al.(2016), insufficient hydraulic design, inadequately sized canals, and unlined earthen channels lead to considerable water losses and swift siltation and poor drainage and degradation of catchment areas further reduce inflows and elevate soil salinity, thereby

2.10.2 Institutional Weaknesses

As stated by Yami (2016), indicate that water user associations (WUAs) typically exhibit low participation rates (60–80%) and ineffective enforcement of bylaws, leading to insufficient operation and maintenance. Conflicting responsibilities among ministries and regional bureaus can postpone repairs by 6–12 months; often resulting in upstream water hoarding that reduces downstream availability by up to 0.5. In most studies show that WUAs also struggle with fee collection less than 0.4 and enforcing rotation equity index is less than 0.6.jeopardizing the sustainability of these schemes.

2.10.3. Socio-economic Barriers

Puchta et al. (2019) and Ulatu et al. (2022), highlight that high input costs, limited access to credit, land fragmentation (0.25–1 ha), and poor market integration negatively impact the profitability of small-scale irrigation (SSI). Limited extension services (1 agent per 500–1,000 farmers) worsen knowledge gaps, and gender disparities persist, with women providing 60% of labour yet holding less than 20% of leadership roles.2.10.4 Regional and Climate Variations

As highlighted by Tadesse et al. (2023) ; Awulachew et al. (2007) and Gebremedhin et al.(2016), insufficient hydraulic design, inadequately sized canals, and unlined earthen channels lead to considerable water losses and sudden siltation. Systems reliant on pumps frequently encounter failures due to maintenance difficulties and fuel shortages, while the efficiency of on-farm irrigation remains notably low (40–50%). As stated by Mekonnen et al., (2020), contend that inadequate drainage and the deterioration of catchment areas further diminish inflows and elevate soil salinity, exposing the sustainability of these systems.

2.11 Strategies for Enhancing the Performance of Small-Scale Irrigation

Strategies refer to deliberate actions or methodologies designed to improve the efficiency, reliability, and sustainability of irrigation systems. Small-scale irrigation (SSI) initiatives frequently encounter various technical, structural, and institutional obstacles that hinder water efficiency, equity, and overall productivity. Studies indicate that merely rehabilitating infrastructure is inadequate; achieving sustainable enhancements necessitates the implementation of integrated technical and management strategies (Molden et al., 2007).

Technical and Structural Measures: The application of canal lining, sealing, and the installation of improved control structures can significantly diminish conveyance losses resulting from seepage and operational spills (Bos et al., 2005). Irrigation scheduling that takes into account crop water requirements, soil moisture levels, and climatic conditions can boost water productivity while reducing waste (Molden et al., 2010). Regular maintenance activities, such as desalting, controlling vegetation, and repairing diversion gates and weirs, are essential for maintaining hydraulic capacity and ensuring equitable distribution (FAO, 1989; 2007).Addressing structural rehabilitation is crucial for aging or poorly designed head works, spillways, and embankments. The integration of sediment exclusion, energy dissipaters, drainage outlets, and climate-resilient strategies (for instance, increased freeboard and stabilized embankments) enhances the reliability and longevity of the system (FAO, 2012). Institutional and Management Measures: Bolstering Water User Associations (WUAs) through legal recognition, well-defined regulations, and capacity-building initiatives can enhance operations, maintenance, fee collection, and conflict resolution (FAO, 1992). Integrated strategies improve efficiency, equity, and productivity in SSI systems while reducing costs and increasing resilience. Overall, sustainable irrigation requires combined technical, structural, managerial, and institutional improvements.

2.12 Research Gaps

Over the last thirty years, approaches to evaluating irrigation performance have evolved considerably. Early contributions by Molden et al.(1990),established fundamental performance indicators adequacy, efficiency, equity, and reliability shifting the focus from theoretical design assumptions to real field conditions. Bos et al.(1994) further refined these concepts by introducing key hydraulic measures, including conveyance efficiency (Ec), application efficiency (Ea), and distribution uniformity (DU). The FAO Penman–Monteith method (FAO, 1997), provided a robust tool for estimating crop water requirements (CWR), enabling systematic comparisons between water supply and crop demand.

In the 2010s, research expanded to include institutional and sustainability aspects. Studies by Awulachew (2010), and IWMI (2015) indicates that, low canal efficiencies and uneven water distribution in many Sub-Saharan African SSI schemes, including Ethiopia. Based on the Hagos et al.(2016), emphasized that the effects of poor institutional coordination and the inequitable allocation of water between upstream and downstream users. Similarly, (FAO, 2017), noted that insufficient monitoring and maintenance often led to deterioration of infrastructure. To address these gaps, this study applies an integrated framework combining technical, operational, and institutional factors to provide a comprehensive, field-based assessment of the Karfe SSI Scheme and support improved irrigation management and sustainability.

2.13 Summary of the literature review

Irrigation performance assessment has evolved significantly over the past three decades, with early studies focusing mainly on hydraulic indicators such as conveyance efficiency, application efficiency, adequacy, equity, and reliability as the foundation for evaluating system performance. (Bos et al. ,1994; Molden et al., 1990). The implementation of the FAO Penman–Monteith method Allen et al.(1998) further propelled the discipline by facilitating precise calculations of crop water requirements (CWR), thus enabling comparisons between water supply and the actual demands of crops. Contemporary research has expanded its focus to encompass institutional, governance, and sustainability dimensions, acknowledging that mere technical efficiency does not guarantee effective irrigation performance (Awulachew, 2010; FAO, 2017; IWMI, 2015). In Ethiopia, SSI systems are constrained by low efficiency, sedimentation, poor infrastructure, weak institutions, and limited farmer knowledge. Most studies assess isolated indicators rather than integrated hydraulic, institutional, and productivity performance. This study addresses these gaps through a comprehensive performance evaluation framework.

3. Research Methodology

3.1 Study Area

3.1.1. Location

The Karfe Small-Scale Irrigation (SSI) initiative Project is situated in the Adaa Woreda,Karfe keble within the East Shoa Zone of the Oromia region in central Ethiopia, nearest to Bishoftu (Debre Zeyit). The project location is nearly 67–74km southeast of Addis Ababa and from Bishoftu by 22km (5km asphalt, 16km gravel road and 1km footpath) positioned at a geographical coordinate of 8.683123° N latitude and 39.093568°E longitude, with an elevation of 2044 meters above sea level.

The Modjo River is a constant tributary of the Awash River located in central Ethiopia, emerging from the Ethiopian Highlands. It flows to the south of Addis Ababa and plays a vital role in the local ecosystem and economy.

This SSI project diverts irrigation water from the Mojo River, constant tributary of the Awash River located in central Ethiopia, emerging from the Ethiopian Highlands. The diversion weir is abroad -crested weir with a crest width of 1.8 m and span of 28 m, designed to provide intake capacity of 0.04 m^3/s. Peak flood design for the river is 155m^3/s, while a 10% downstream release is maintained for ecological and downstream needs (design document).The irrigation water is transported through a system of lined both sides. The left lined MC length is 1500m (1.5km) and the right MC length is 2810 (from this 500m unlined MC), which directly applies water for tertiary canals then it, distributes the water to the individual farm plots. The scheme structure components including: 2 non-functional under-slices gates,2 head regulators (right side is non- functional), 2 side retaining walls (left side is failed), accessory road over the weir,6 box culverts crossings and one flume structure at the right MC (aqueduct structure) which indicates MC water passes over natural drainage.

The project is structured to function using surface irrigation techniques, providing water to smallholder farmers in a semi-humid tropical climate characterized by annual minimum rain fall, predominantly occurring between June and September, and a mean annual temperature ranging from 11.42 to 26.3083°C.The Karfe SSI scheme covers a command area of 65 hectares, benefiting around 162 smallholder farmers. The crops cultivated include potatoes, tomatoes, onions, cabbage, and lettuce, primarily for local markets, but during the study period the field was covered 80% by Wheat crop.

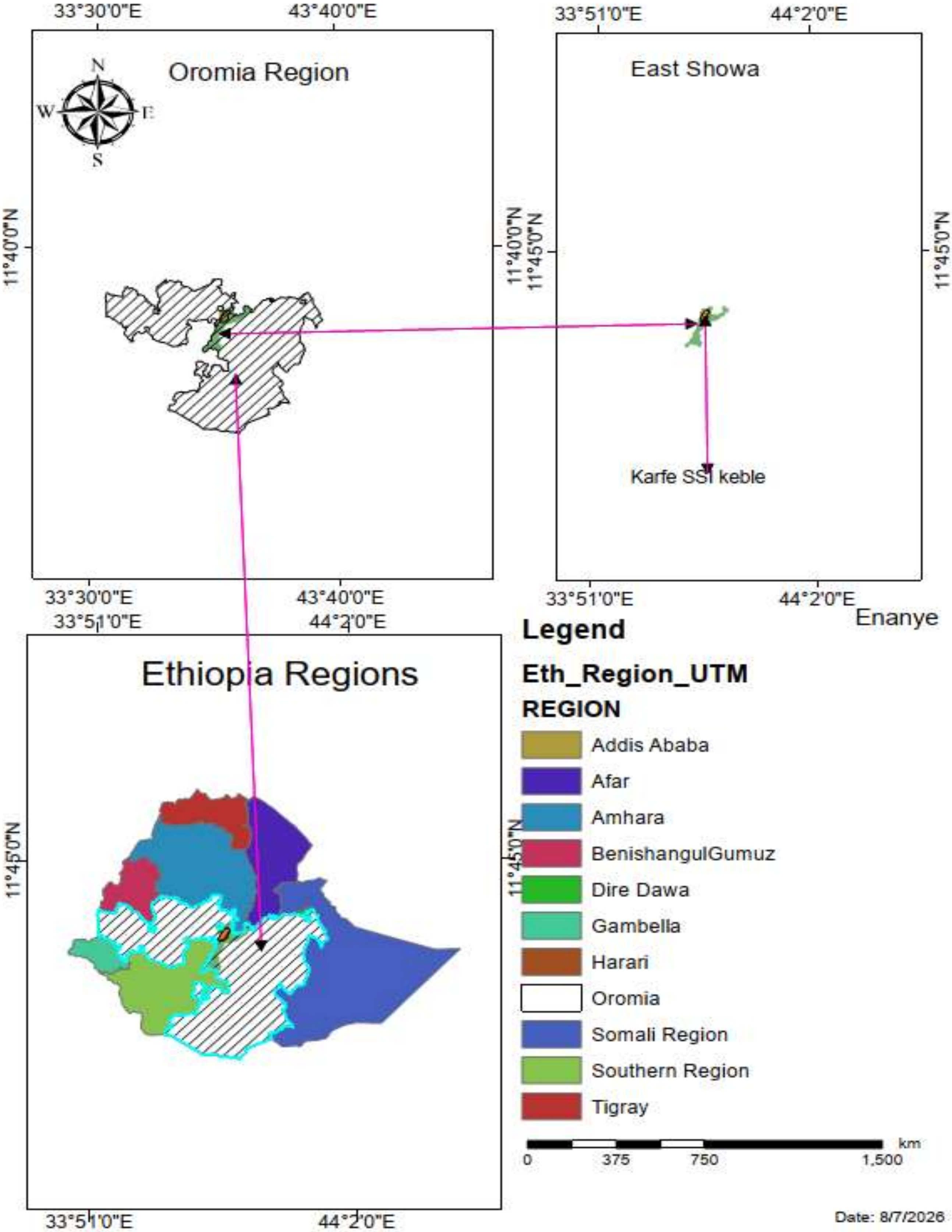


Figure 1: Study area map location.

3.1.2 Climate

According to the Bishoftu Meteorological Station, the average monthly rainfall fluctuates between minimum 8 mm in January and maximum 230 mm in August. The mean monthly relative humidity ranges from 43% to 72%, with an average of 56.17%. Wind speeds vary from 52 to 130 km/day, while the number of sunshine hours spans from 5.4 to 8.9 hours per day and the solar radiation 17.1 to 22.3MJ/m^2/day. Monthly temperatures are recorded between 5.6°C in December and 28.4°C in March.

The results indicate that the mean monthly minimum and maximum temperatures are 11.38°C and 26.31°C, respectively. The relatively moderate temperature range suggests favourable conditions for crop growth throughout the year. Seasonal variation is evident, with slightly higher temperatures observed during the dry months, which contributes to increased evapotranspiration demand.

The Evapotranspiration (ETO) varies from 99.9mm/month to 136.5mm/month. Maximum ETo values are observed from February to May, primarily due to higher temperature, radiation, and sunshine hours, whereas lower values occur during the rainy season due to increased cloud cover and humidity.

Rainfall in the Karfe area is highly seasonal, with an annual total of 490.2 mm. The majority of rainfall occurs during July and August, with monthly totals of 178 mm and 230 mm, respectively. Effective rainfall follows a similar trend, reaching a maximum of 160 mm in August. During these peak rainy months, effective rainfall is sufficient to meet or even exceed crop water requirements.

Effective rainfall during January, October, November, and December, is zero this explains that there is no rain that meets the crop water requirement. Therefore this gap is substituted by application of irrigation water due to this the SSI scheme development was basic solution

In general Karfe rainy months are very short period from June to August, so irrigation has basic role in the aerator supplement the wet season crops and to increase productivity during the next dry seasons of the month 9

In summary, the analysis reveals a significant discrepancy between water supply and crop water requirements throughout the majority of the year. This underscores the vital role of irrigation, especially in the dry season, and establishes a solid foundation for irrigation planning, system design, and water resource management in the region. Those Karfe irrigation scheme climatic properties are represented as in the following graphs.

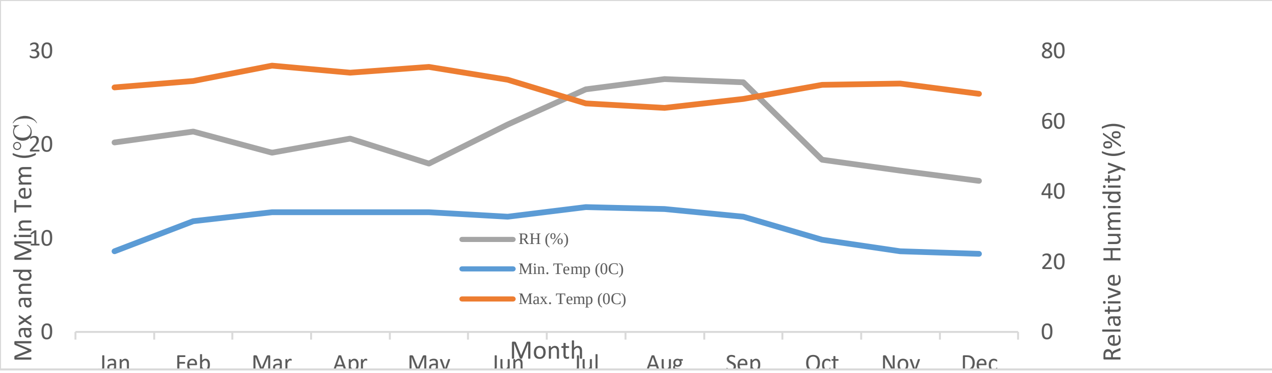


Figure2: Average monthly min, max temperature and relative humidity for the scheme

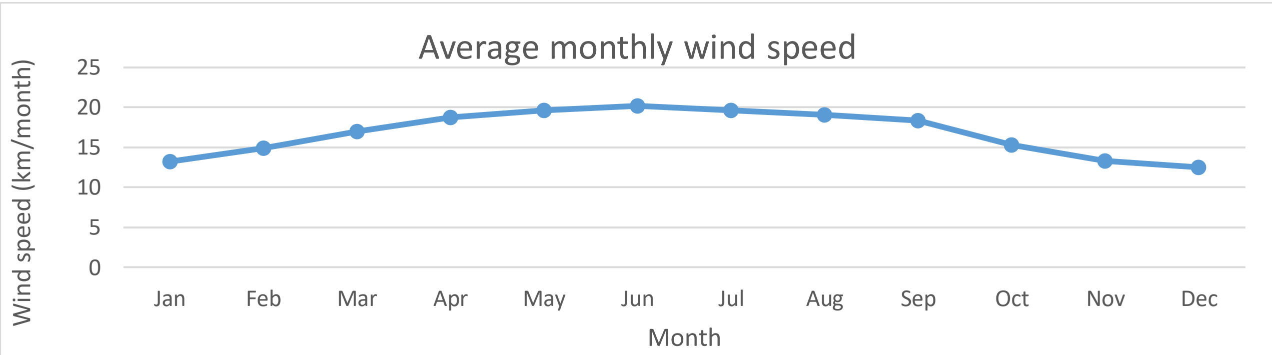
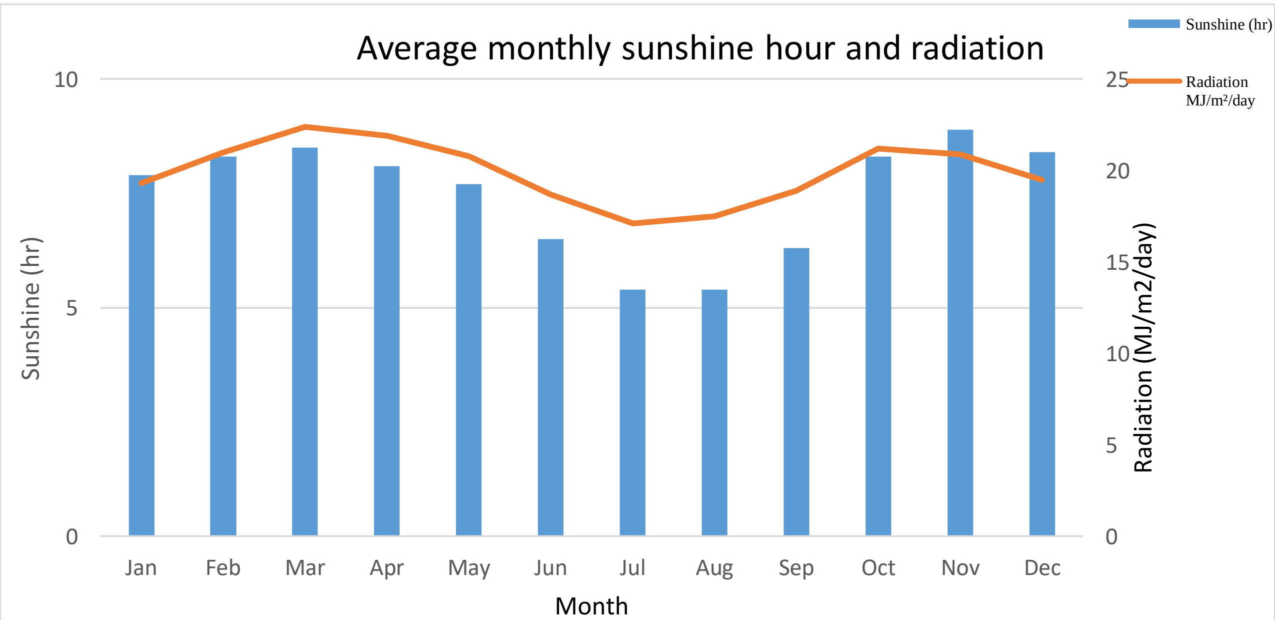


Figure 3: Average monthly wind speed for the scheme



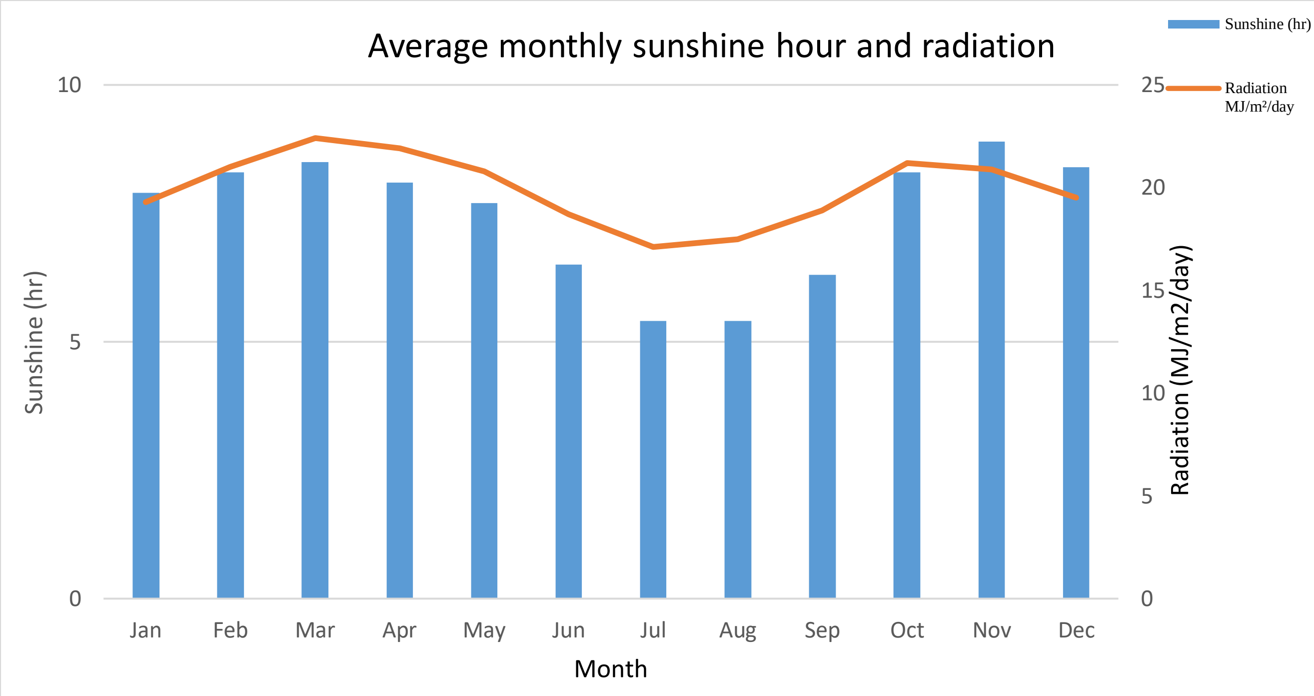


Figure 4: Average monthly sunshine hour and solar radiation of the scheme

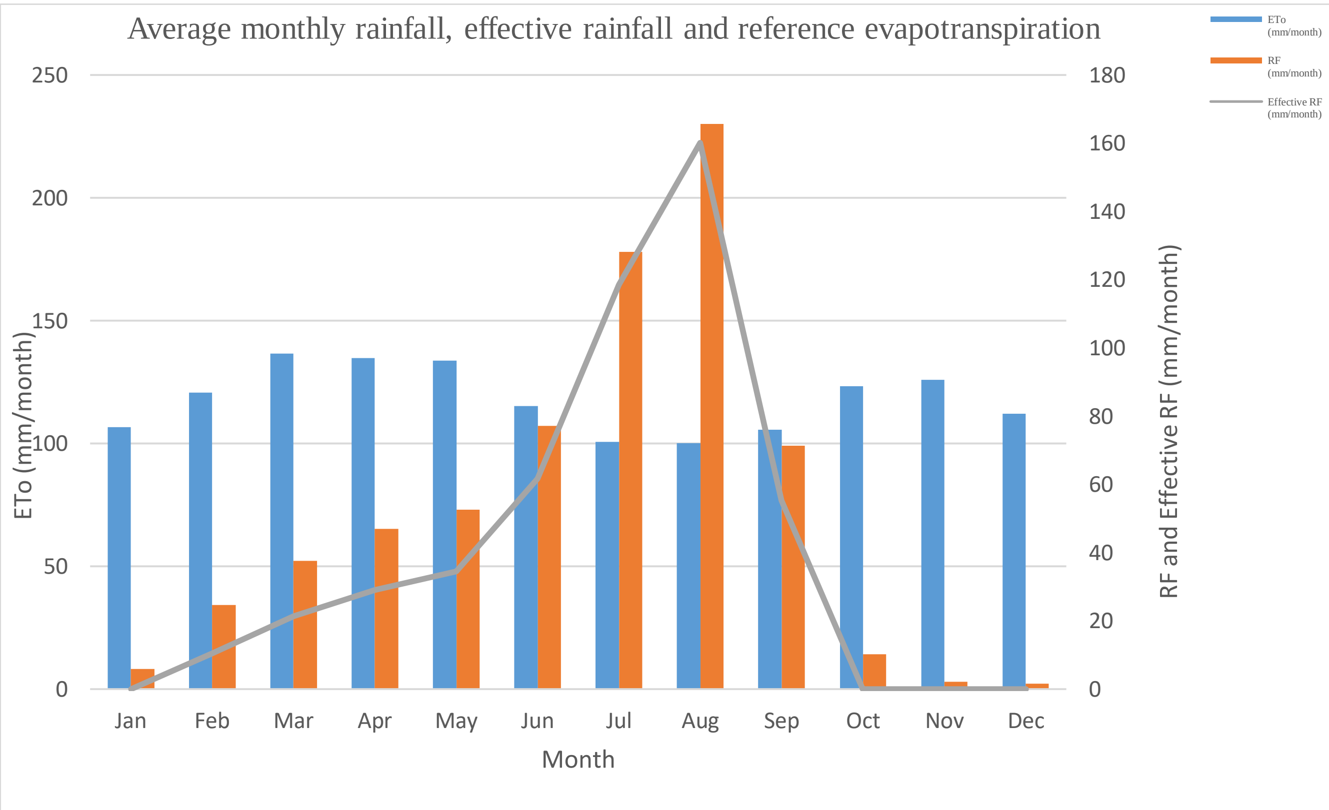


Figure 5: Average monthly rainfall, effective rain fall and R. ETo of the Scheme

3.1.3 Topography

The landscape features a gently rolling topography, characterized by slopes that vary between 2% and 8%, which is advantageous for gravity-fed irrigation systems. The soil composition is mainly clay to salty clay, exhibiting a fundamental infiltration rate of around 12 mm/hr from design document, which affects both water retention and the planning of irrigation schedules.

3.1.4 Population

The Karfe small irrigation scheme is situated at Karfe kebele in Adaa Wreda, consists of 4 communities which are Chirmo, Ofu &Tame and Karfe. Based on the data obtained from the keble development office, indicates that about 8,928 populations live in the Karfe kebele, from those about 4868 (54.53%) are male and the rest of 4060 (47.45%), populations are Female. The total number of household in the community is about 1222, from this 86.25% male-headed and 13.75% female headed households.

Table 3.1 Household Distribution by Community in Karfe Kebele

No	Community	Male	Female	Total	Percentage distribution by administrative unit (%)
1	Ofu & Tamae	311	46	357	29.21
2	Karfe	354	58	412	33.72
3	Chirmo	389	64	453	37.07
	Total	1054	168	1222	100

As indicated above table the community percentage of distribution by administrative of Ofu&Tame,Karfe and Chirmo is 29.21%,33.72 %, 37.07% respectively.

3.1.5 Soil type

The Karfe SSI area is dominated by Vertisol soil, a heavy clay type with high shrink–swell behavior and water-holding capacity but poor drainage. Soil analysis (55.39% clay, 25.91% silt, 18.69% sand) classifies it as clay, indicating high moisture retention and plasticity when wet.

3.1.6 Land use land cover

The land cover of the area is primary influenced by climate, particularly the short rainfall period mostly from April to August and high temperature. The study area is dominated by intensively cultivated land employed for seasonal crops like teff, Wheat, chickpea and vegetables such as Onion, tomato, potato and cabbage are major cultivated cops by irrigation scheme. While irrigated crops are dominated by wheat (80%) followed by Cabbage (11%) and potato (9%). In addition, limited portion of land is covered by grasses for grazing, rocks and open bushes. The area is affected by land degradation due to low concern of soil water conservation works in the area.

3.2 Materials used during the study

The research employed a range of materials and hydraulic measurement tools for the collection of field data and soil sampling. This encompassed devices for measuring flow, including the float method, volumetric bucket, and a V-notch weir, all of which were utilized to accurately ascertain discharge throughout the duration of the study.

Table3.1: Materials used during the data collection and analysis.

Type	Materials	purpose
Material	Plastic float	To assess the velocity of flow in the river and the MC canal
Material	Field notebook	To document the measurements, observed, viewed, sketches
Material	Auger	To collect disturbed soil samples from the field
Material	Core sampler	To obtain undisturbed soil samples for laboratory analysis
Material	Plastic bag	To store and transport collected soil samples
Material	Bucket	To measure discharge using the volumetric method
Material	Wooden Stakes	To identify and designate the measurement points for flow and cross-sectional assessments in rivers and canals.
Equipment	Stopwatch	To time the duration for the float to cover a specified distance and application time.
Equipment	Measuring tape (50m)	To gauge the width and depth of the river, canals and farm dimension the for cross-sectional area calculations
Equipment	Water Level	To assess water levels and gradients in canals and river sections
Equipment	GPS	To measure places coordination
Equipment	Smartphone	For photographic documentation of the research area and instruments
Software	Microsoft Excel	For data entry, calculations, and analysis of hydrological parameters
Software	CROPWAT 8.0 With Clime	To compute reference evapotranspiration (ETo), crop water requirements, and net irrigation needs.
Software	ArcGIS	For mapping the irrigation system
Software	Medley	To referencing

3.3 Methods Used

This research employed both primary and secondary data sources. Primary data were obtained directly from the field through various measurements, including canal discharge using (v-notch weir, floating and volumetric bucket), water levels, and soil samples at three for laboratory analysis, field plot assessments, and interviews with farmers, and direct observations of irrigation infrastructure. Secondary data were collected from Karfe Keble administration and Adaa worda Agriculture and land office and Bishoftu meteorological station and pre-existing design documents pertaining to the Karfe irrigation scheme.

3.3.1 Primary Data

The primary data for this research were obtained through direct field investigations and laboratory analyses. These encompassed measurements of canal discharge utilizing the V-notch weir, volumetric method, float method, and cross-sectional measurements; monitoring of water surface elevation along the main canal; soil sampling to determine moisture content, bulk density, and texture analysis; evaluation of the conditions of irrigation structures; and documentation via GPS and photographs. Furthermore, information regarding beneficiary farmers, irrigation scheduling practices, and water management was collected through questionnaires, Key Informant Interviews (KIIs), and Focus Group Discussions (FGDs). The comprehensive procedures, locations of measurements, and timing of data collection are detailed in the following sections.

I. Flow measurement

To assess the adequacy and spatial distribution of irrigation water, daily discharge measurements were conducted at River and at designated control points along the primary canal. The main measurement sites included: The river u/s of the weir, the diversion weir, and the tail-end outlets of the main canal at upstream, middle, and downstream sections, at off takes and fields of selected sections. The procedure for measuring discharge comprised the following systematic steps.

A). River discharge using Floating method was assessed at a segment of the Mojo River situated roughly 10 m upstream of the diversion weir to know amount of water flow during the study season. The float method was used to the measurement. During the field measurement, two wooden stakes, 10 m measuring tape, ruler, Floating plastic ball and Smartphone stopwatch.

The discharge measurement was conducted by applying the following steps:

1. Selection of a straight and uniform river section was chosen to guarantee steady and non-turbulent flow. The reach was free from vegetation obstructions, and excessive turbulence.

2. Marking the Measurement Section two wooden stakes were installed to delineate the start and end points of the selected reach. The distance (L) between the two reference sections was accurately measured using a 10m measuring tape.
3. The floating plastic ball was released slightly upstream of the first marked section to enable it to attain uniform velocity. The time (t) taken for the float to traverse the measured distance (L) was recorded using a smartphone stopwatch. The measurement was repeated three times (at left, centre and right side of the river) and Surface velocity (Vs) was calculated using: $V\ s = \frac{\text{L}}{\text{t ave}}$ in (m/s).Due to surface velocity exceeds the mean velocity, a correction factor of K value range from 0.8-0.9 was utilized based on the (FAO, 1992) and take the average of them K= 0.85: $V\text{ave} = \text{K} \times Vs = 0.85V_s$.
4. Measurement of River Cross-Section At the upstream reference section: The river width (b) was gauged using the 5m measuring tape. Flow depth was recorded at regular intervals across the section with a staff-gage. The average depth (y_{ave}) was computed. The cross-sectional area (A) was determined as: $A = b \times y_{\text{ave}}$
5. The river discharge Q (m3/s) was computed using: $Q = A \times V_{\text{ave}}$.

B). Canal Discharge using float method**:** At the intake, upstream, middle, and tail sections of the lined main canals to analyse flow reduction and conveyance efficiency. A straight, uniform reach was chosen at each section, and three lateral points (left, centre, and right) were utilized to capture the velocity distribution across the canal. Materials utilized two wooden stakes 20 m measuring tape, staff-gage (for depth measurement), floating plastic ball, Smartphone stopwatch.

Procedure

1. Selection of a straight and uniform canal section to guarantee steady and non-turbulent flow. The reach was free from vegetation obstructions, and excessive turbulence.
2. Marking the Measurement Section two wooden stakes were installed to delineate the start and end points of the selected reach. The distance (L) between the two reference sections was accurately measured using a20m measuring tape.
3. The floating plastic ball was released slightly upstream of the first marked section to enable it to attain uniform velocity. The time (t) taken for the float to traverse the measured distance (L) was recorded using a smartphone stopwatch. The measurement was repeated three times (at left centre and right side of the canal) and Surface velocity (Vs) was calculated using: $V\ s = \frac{\text{L}}{\text{tave}}$ in (m/s).Due to surface velocity exceeds the mean velocity, a correction factor of K value range from

0.8-0.9 was utilized based on the FAO (1992) and Chow, V.T (1959) statement, taken the average value of K = 0.85: Vave = K× Vs =0.85Vs.

4. Calculate the wetted area by measuring the canal width (b) and depth (y_{ave}) in meter.
5. The river discharge Q (m3/s) was computed using: $Q = A \times V$ave.

C).Volumetric Bucket Method:

The discharge from the main canal to the fields was quantified using the volumetric method (for small flows) at three off-takes at head, middle and tail sections in order to compare water distribution equity in the section. A 20 litter bucket positioned and aligned with the ground surface beneath the off-take outlet to ensure precise water collection by gravity pressure. The duration (t) necessary to fill the container was measured with a stopwatch and the process was repeated multiple times, and the average filling time was utilized to determine the discharge. This method is widely recommended for measuring small discharges in field irrigation studies (Jensen, 1983; Walker et al., 1987).Procedures

1. Position 20 litters volumetric bucket with the ground surface beneath the off-take outlet.
2. Measure the time (t) required to fill the volumetric bucket using a stopwatch.
3. Repeat the measurement two times and calculate the average time.
4. Determine discharge using $Q = \frac{\mathrm{L}}{\mathrm{tave}}$ in (l/s) and convert in to (m3/s) by multiply 10^{-3}.

II. Actual Water level measurement (AWL)

To evaluate conveyance system performance along the main canal (MC) during the irrigation time, water surface elevations were measured at 20 m intervals from the intake to the canal end using staff-gage and measuring tape. Measurement locations were distributed across the three reaches for comprehensive analysis of water distribution along the sections to compare. During this time additionally observes the scouring, silt deposition and accumulation, seepages, cracks, missed structures external impacts conditions and measure the existing dimensions of the system.

III. Soil sampling

Soil samples were obtained from various depths within the chosen field plots. The samples underwent air-drying and sieving. A specific quantity of soil was combined with water in a measuring cylinder, thoroughly shaken, and allowed to settle for 24 hours. Upon settling, distinct layers of sand, silt, and clay emerged. The height of each layer was recorded, and the percentage of each particle type was computed by dividing the height of each layer by the total height and multiplying the result by 100. These calculated percentages were subsequently applied to the soil texture triangle to ascertain the soil textural classification.

Undisturbed soil samples were collected from different depths using a core sampler to determine bulk density. Soil samples for moisture content were collected at 30 cm intervals down to a depth of 100 cm. This depth corresponds to the effective root zone of the main irrigated vegetable crops in the area, with the maximum root zone for onion and tomato being 100 cm (FAO, 2017). Soil moisture content was measured using the gravimetric method.

Samples were taken from selected field plots at different depth intervals along the soil pit using appropriate tools. The collected samples were analysed to determine bulk density, soil texture, soil moisture content, field capacity, permanent wilting point, and other soil properties. Plots were selected based on water availability from the conveyance system and distance from the water source to the command area.

IV. Field observations

Throughout the field observation, every irrigation structure from the upstream to the downstream was examined, taking into account their condition, any cracks, seepage, sedimentation, and blockages. Instances of missing or damaged structures were documented, along with the various types of irrigation methods utilized across different fields. Conditions of the fields, such as areas that were logged or eroded, soil moisture levels, and crop coverage, were meticulously recorded, and various crop types along with their growth stages were noted. The purpose of the field observation was to assess the condition and functionality of irrigation structures, evaluate water distribution efficiency, and record field conditions, irrigation methods, and crop types to identify problems and guide improvements.

V. Questionnaires and Interviews

Structured questionnaires and interviews were conducted with farmers chosen from the upstream, midstream, and downstream areas of the irrigation scheme through stratified random sampling. The objective was to gather information regarding irrigation frequency, duration, decision-making criteria, and farm-level control methods. The questionnaires were supplemented by informal discussions to explain the responses.

VI. Key Informant Interviews (KIIs)

Key Informant Interviews were performed with leaders of Water User Associations (WUAs), scheme operators, and local experts from the Bishoftu Adaa Agriculture and Land Office, as well as the administrations of Adaa Woreda and Karfe Kebele. The purpose of the KIIs was to obtain comprehensive information regarding scheme management, maintenance schedules, water allocation, and operational challenges. The interviews adhered to a semi-structured guide, and the insights were thematically summarized to enhance the survey data.

VII. Focus Group Discussions (FGDs)

Focus Group Discussions were convened with leaders of irrigation user groups to gather collective perspectives on irrigation practices, water conflicts, crop management, and local solutions. Each group comprised 6–12 participants. The discussions were facilitated using guiding questions, and key points were documented and thematically analysed to identify recurring issues and recommendations for enhancing irrigation management.

VIII. Photographic and GPS

This documentation was conducted to capture the physical state of irrigation structures, field areas, weir components, crops and the spatial arrangement of the scheme. Key locations, including the head, middle, and tail sections, were mapped using GPS coordinates. Photographs recorded the conditions of canals and operational challenges such as siltation, seepage, or damaged structures external impacts. Geospatial positioning system (GPS) and photographic information were utilized to enhance spatial analysis, evaluate irrigation distribution, and corroborate field observations.

IX. Sampling Method

A random sampling method was used to select farmers from the irrigation schemes to complete structured questionnaires on the scheme performance evaluation. The sample size of farmers were determined using (Yamane's, 1967), which was selected due to its simplicity, transparent, and widely applied in agricultural and irrigation research in Ethiopia. Using farmers (households) (N) and 10% precision level (e). Applying the formula sample size (n) = N/ (1+N (e^2)) then, gives 62.

3.3.2 Secondary Data sources

Secondary data were gathered from project documents, official reports, and previous studies journals, standards FAO and IWMI to enhance the study. This data encompassed the design and configuration of the Karfe Small-Scale Irrigation Scheme, water control structures, the area under irrigation, and the number of farmers, sourced from the local agricultural office and adaa woreda Agriculture and land administrative office.

Climatic and Meteorological Data: Climatic data from the Bishoftu Meteorological Station served as a reference for the Karfe Keble. The area experiences a warm climate characterized by distinct wet and dry seasons: The average annual rain-fall is 72.08 mm, with the primary rainy season occurring in July–August and a dry spell from December to February. The monthly minimum temperature ranges from 8.3°C to

13.3°C, while the maximum ranges from 23.9°C to 28.4°C. Relative Humidity ranges from 43% to 72%, with an average of 56.17%. Wind Speed varies from 299.3 to 484.6 km/day, with an average of 403.5 km/day. Sunshine lasts between 5.4 to 8.9 hours/day, averaging 7.48 hours/day. Solar Radiation ranges from 17.1 to 22.4 MJ/m²/day, with an average of 19.93 MJ/m²/day. These climatic conditions indicate that irrigation is crucial to compensate for the inadequate and irregular rainfall

3.4 Data Analysis method

Data collected from field measurements, laboratory analyses, and farmer surveys were analysed using quantitative and qualitative methods. The irrigation scheme was evaluated at the head, middle, and tail sections and compared with FAO and IWMI performance standards. The assessment focused on water supply adequacy, conveyance and distribution efficiency, structural performance, and irrigation management practices. Soil samples and field data were collected from representative plots located at the head, middle, and tail reaches. Field measurements were analysed using standard irrigation engineering formulas and performance indicators, while survey data were summarized using descriptive statistics, including percentages, tables, and graphs.

3.4.1 Analysis of Water Supply Adequacy

Water supply adequacy was evaluated to determine whether the irrigation system delivered sufficient and reliable water to meet crop water requirements throughout the irrigation season. Crop water requirements for the 65 ha command area were estimated using CROPWAT 8.0, while actual canal discharges were measured using the area–velocity method. Performance indicators, including the Supply Adequacy Ratio (SAR), Reliability Index (RI), and Dependability Ratio (DR), were computed by comparing the supplied water with crop water demand. Soil properties, soil moisture measurements, crop water requirements, and actual water deliveries were integrated to assess the adequacy, reliability, and effectiveness of water management within the irrigation scheme.

3.4.1.1 Soil Moisture Content Measurement

In this research, the measurement of soil moisture was essential for assessing the sufficiency and dependability of the water supply within the Kafe Small-Scale Irrigation Scheme. By conducting soil moisture assessments prior to and following irrigation across three distinct plots and at three different depths (0–30, 30–60, 60–90 cm), the study effectively quantified the water retained within the crop root zone, identified field capacity and wilting point, and calculated the total available water. These measurements facilitated the evaluation of application efficiency, irrigation performance, and the effectiveness of water management, thereby ensuring that crops received adequate water while minimizing losses and promoting optimal irrigation scheduling by follows widely accepted procedures described by ((FAO, 1989; 2007); Haoxing et al, 1998; Misra et al., 1997).

This section outlines the experimental methodology for measuring soil moisture, determining soil physical characteristics, and calculating water availability within the root zone, performed across three representative plots of the irrigation system. The aim of this experiment was to quantify soil moisture content at various depths and locations.

A) Measurement of Soil Moisture Content

Measure or determine how much water remains in the soil within the crop's root zone after an irrigation event were used to calculating the application efficiency, field capacity, permanent wilting point, and total available water. During the study, field and laboratory analyses were conducted using standard equipment, including a soil auger for sample collection, pre-weighed moisture containers lined with strong aluminium foil, a precision hand balance for weighing, an oven maintained at 105°C for drying samples, and labelling materials for sample identification. Soil sampling was carried out at three representative locations along the canal command area, namely the head, middle, and tail sections, to capture spatial variability in soil properties. Samples were collected at depth intervals of 0–30 cm, 30–60 cm, and 60–90 cm, representing the upper, middle, and lower portions of the effective crop root zone. These depths were selected to evaluate soil moisture distribution, storage characteristics, water movement, and plant-available water, which are essential for assessing irrigation performance and water management efficiency(Allen et al., 1998b).Sampling was conducted under two conditions: before irrigation to determine the initial soil moisture status and 24 hours after irrigation to allow gravitational drainage. Bulk density was determined using a 3 × 3 (plots × depths (0-30-60-90cm)) sampling design, yielding 9 samples, the soil physical properties was determined by taking 3 × 3 (points× plots) resulting 9 mixed sample, Soil moisture content was determined using the gravimetric oven-drying method at 105°C as described by Gardner (1986), applying a 3 × 3 × 2 (plots × depths(0-30-60-90cm ×after &before) irrigation scheme, resulting in 18 samples, distribution uniformity (DU) was evaluated using 3 × 3 samples from the(0–90 cm) root zone at head, middle, and tail positions, giving 9 samples. Application efficiency was also assessed using 3 × 3 (plots × depths (0-30-60-90cm)), resulting in 9 samples. All soil samples were collected using a soil auger and immediately stored in labelled containers to prevent moisture loss during transport. In total, 54 soil samples were collected and analysed for the study. The moisture boxes were weighed prior to adding soil to obtain the empty box weight (W1, g). A 100 g of fresh soil was added to each box, and the combined weight was recorded as wet weight (W2, g).

B) Determination of Soil Physical Properties

i. Soil Texture

In order to assess soil texture, nine composite disturbed samples were gathered from various field sites. The distribution of soil particle sizes was analysed in the laboratory, and the classification of soil texture was determined utilizing the USDA soil textural triangle (Mwendwa, 2020).

As stated by USDA the soil texture triangle serves as a graphical tool for classifying soils according to the relative amounts of sand, silt, and clay present. Each vertex of the triangle signifies 100% of a specific particle size: sand, silt, or clay. By plotting the percentages of these fractions, one can categorize the soil into one of 12 primary textural classes, such as loam, sandy loam, clay loam, and salty clay, Clay, among others. Procedure:

1. Calculated percentages of sand, silt, and clay in the soil sample through laboratory techniques.

2. Identify the point on the triangle by adhering to the scales for sand, silt, and clay.

3. The area of intersection indicates the soil textural class.

ii. Bulk Density

The bulk density was assessed using nine undisturbed soil samples obtained from three pits, utilizing core samplers with a volume of 98.4 cm^3 at intervals of 30 cm each. The samples were subsequently placed in an oven and dried at a temperature of 105°C for duration of 24 hours. Following the drying process, both the soil and the container were weighed again. The dry weight of the soil was then divided by the sample volume to calculate the dry bulk density. The dry bulk density (ρb) was determined by dividing the oven-dry mass of the soil sample (Md) by the known volume of the core sampler (Blanke, 1992-1992), as expressed in the following equation:

$$\rho b = \frac{Md}{Vb}$$ --Equation (3. 1).

where: ρb = bulk density (g cm^{-3}) md = oven-dry soil mass (g) Vb = volume of core sampler (cm^3) Bulk density plays a crucial role in the transformation of gravimetric moisture content to volumetric moisture content, as well as in assessing soil compaction and its capacity for water storage (Hillel, 2002).

iii. Field capacity, Wilting point, and Soil water availability

Soil moisture levels at field capacity (FC) and permanent wilting point (PWP) were assessed through disturbed soil samples taken from three distinct locations head, middle, and tail at intervals of 30 cm depth. To evaluate the total available water (TAW) within the soil, both FC and PWP were used to determine the gravimetric method, which is economical, easily accessible, and yields reasonably precise laboratory estimates of soil water content.

For the determination of FC, soil samples were gathered after 24 hours following irrigation, reflecting near-saturated conditions. The wet samples were weighed to ascertain the wet weight (Wwet) and subsequently oven-dried at 105°C for 24 hours to determine the dry weight (Wdry). Gravimetric moisture content (GMC) was computed using Equation 3.3, and converted to volumetric moisture content (θv) utilizing the measured bulk density (BD) of the soil (Equation 3.1).

The volumetric moisture content was designated as FC for each soil layer, indicating the maximum water content accessible to crops post-irrigation. In a similar manner, PWP was established using pre-irrigation soil samples, which represent the driest soil condition where plants can no longer extract water. The wet and dry weights of the samples were recorded, GMC was calculated (Equation 3.3), and converted to volumetric moisture content using bulk density. The resulting volumetric moisture content was documented as PWP for each soil layer, denoting the lower threshold of plant-available water. Utilizing the measured values of FC and PWP, the available water content (AWC) for each soil layer was computed as the difference between FC and PWP .Total available water (TAW) was derived by multiplying AWC by the depth of each soil layer (Equation 3.4), while readily available water (RAW) was estimated using standard depletion fractions suitable for the crop.

All laboratory analyses were performed at the Bishoftu Soil Laboratory Centre, utilizing standard field and laboratory equipment such as a soil auger, soil moisture boxes, an oven, and an analytical balance. This approach facilitated a practical and precise evaluation of soil water availability across various field locations and soil depths, thereby directly aiding the assessment of irrigation performance in the study area.

Laboratory Procedures:

1) Collect soil samples from the area where the plant leaves exhibit signs of wilting.
2) Utilize a soil auger to extract samples from specified depths beneath the ground surface and place them in moisture boxes.
3) Measure the weight of the empty moisture box (W1), in grams.
4) Weigh each soil sample (approximately 100 grams) together with the moisture box (W2), in grams.
5) Place the soil samples along with the boxes in an oven for 24 hours at 105°C.
6) Measure the weight of the dried soil sample with the box (W3), in grams.
7) Calculate the soil moisture content based on the percentage of weight.
8) The gravimetric soil moisture content (MCw), representing water content relative to dry soil mass, was calculated using the formula:

$$GMW_C = \frac{(W2-W3)}{(W3-W1)} * 100$$ --- equation (3.2).

Where: GMWC represents the gravimetric soil moisture content (%). W1 denotes the weight of the empty moisture box (g). W2 indicates the weight of the wet soil along with the box (g). W3 signifies the weight of the dry soil in addition to the box (g).

The volumetric moisture content (MCv) represents the actual volume of water per unit volume of soil and was calculated by multiplying the gravimetric moisture content by the soil bulk density (BD):

$MCv = GMW_C \times BD$--equation (3.3).

Where: BD ($g\ cm^{-3}$) was determined from undisturbed soil cores collected at the same depths.

The total available water (TAW) represents the amount of water that can be stored in the root zone and used by the crop. It was calculated using volumetric soil moisture content at field capacity (FC) and permanent wilting point (PWP), following (FAO, 1989; 2007).

$TAW = (FC-PWP)*Zr*1000$ --equation (3.4).

Where: TAW is Total Available Water in the root zone (mm), FC is water content at field capacity (m3/m3), WP is water content at wilting point (m3/m3),and Zr is Rooting depth (cm) Following the drying process, both the soil and the container were weighed again, allowing for the determination of water weight based on pre- and post-measurements.

Readily Available Water (RAW)

$RAW = p*TAW$ --- equation (3.5).

Where: p = depletion fraction

The soil moisture depletion fraction (p) signifies the ratio of available soil water that is utilized by the crop root zone in the interval between irrigation events. It reflects the volume of water that plants draw from the soil prior to the necessity of irrigation to prevent water stress.

B) Amount of Water Applied to the Field

To determine the amount of irrigation water applied to the selected fields, the flow rate entering each experimental plot was measured using a volumetric bucket method at the field off take. The volume of water collected in the bucket and the time required to fill the bucket were recorded using a stopwatch in order to calculate the discharge rate. During irrigation, the total irrigation duration was also recorded until the water reached the end of the furrow. The length and width of each irrigated plot were measured using a measuring tape to determine the area of the field.

Based on the measured discharge rate, irrigation duration, and area of the irrigated plot, the depth of water applied (Wf) to the field was computed using the following equation (Allen, 2000; Burt, 2004).

$$Wf = \frac{Q*t}{A}$$ -- equation (3.6).

Where: Wf is depth of water applied to the field (mm),Q is flow rate or discharge at the field off take (m^3/s),t is irrigation duration (s) and A is area of the irrigated plot (m^2).

1. Application Efficiency

Application efficiency indicates the percentage of irrigation water that is stored in the crop root zone and becomes available for plant use. It is an important indicator for evaluating irrigation performance. During this time taking soil sample before the irrigation from the three sction s and after irrigation of measured discharge in the filed taking soil samples from three section to compute the stored moisture in the root zone .

The application efficiency (Ea) was calculated using the following equation(Howell et al., 1997):

$$Ea = \frac{ws}{wf}*100$$ ---equation (3.7).

Where: Ea is irrigation application efficiency (%); Ws is water stored in the soil root zone (mm) & Wf is water applied to the field (mm). The efficiency was determined for each furrow and subsequently averaged across each plot to reflect the overall irrigation performance of the field. And the storage efficiency the ratio of stored to net required in the root zone (Fc-θi)×Zr*1000.

3.4.1.2 Actual supplied flow measurement

The actual discharge of the irrigation system was measured along the main canals from the intake to the downstream end of both the left and right canals to determine water availability for irrigation. Measurements were conducted at representative head, middle, and tail sections using the area–velocity method. Canal width, water depth, and flow velocity were measured at selected straight and uniform canal reaches using a measuring tape, meter ruler, floating object, and stopwatch. The collected data were used to determine canal discharge and assess water distribution performance throughout the irrigation scheme(Allen, 2000; FAO, 1992; Moldenet al., 1990). Flow velocity was measured using the floating method, where a plastic ball was released on the water surface and the time required to travel a known distance was recorded. Each measurement was repeated three times to reduce errors, and the surface velocity (Vs**)** was calculated as: $Vs = \frac{D}{T}$, where: D is the distance travelled by the floating object (m) and T is the travel time (s).

A correction factor (K=0.85 for lined canals) was applied to account for velocity variation along the depth, giving the mean flow velocity (V**)** (Allen, 2000; R. S. Burt, 2004)as:

$V = K \times Vs = 0.85\ Vs$-- equation (3.8).

At each measurement section, the canal width (b) and flow depth (y) were measured to determine the cross-sectional flow area (A) using b*y. Then the rectangular canal discharge (Q) was then calculated using the area–velocity method:

$Q = A \times Va$---equation (3.9).

These discharge measurements at multiple sections along the canal were later used to estimate the daily and monthly average discharge of both left and right main canals. The net available discharge (Q_{Net}**)** for the irrigation system was obtained by summing the discharges of the two canals:

$Q_{Net} = QL + QR$-- equation (3.10).

Where: QLand QR represent the discharge of the left and right canals, respectively. To evaluate water losses, the conveyance efficiency (Ec) of the canal system was calculated as:

$Ec = \frac{Qout}{Qin} * 100$ -- equation (3.11).

Where Qout and Qin are the downstream and upstream discharges, respectively.

3.4.1.3 Estimation of Crop Water Requirement (CWR)

The crop water requirement (CWR) was calculated to ascertain the volume of water necessary for 52ha wheat, 6ha of cabbage and 7ha of tomato crops growth during this study on the farm 80%, 11% and 8% respectively in each plot area of head, middle and tail, within the irrigation command area and to evaluate the sufficiency of water supply. Seasonal irrigation needs were contrasted with the actual water distributed in the fields to determine the crop water demand.

Climatic data, which encompasses monthly maximum and minimum temperatures, relative humidity, wind speed at a height of 2 meters, sunshine hours, and rainfall, were sourced from the Bishoftu Meteorological Station. Crop data, including crop type, planting and harvesting dates, growth stages, crop coefficients (Kc) and rooting depth, were acquired from the CROPWAT crop database and FAO guidelines. Soil characteristics, such as soil texture, field capacity (FC), permanent wilting point (PWP), and total available soil moisture, were assessed through laboratory analysis of soil samples collected from the study area. These input parameters were utilized in CROPWAT 8.0 to calculate crop evapotranspiration and crop water requirement (CWR) for the irrigation scheme(Allen et al., 1998b).

Once all necessary input parameters were inputted into CROPWAT 8.0, the software produced outputs such as reference evapotranspiration (ETo), crop evapotranspiration (ETc), effective rainfall, net and gross irrigation water requirements and seasonal crop water requirement.

Procedures

To this calculation using the above data parameters the crop water requirement was performed in several steps using CROPWAT 8 as the following.

1.Reference evapotranspiration (ETo) through the application of the FAO Penman–Monteith equation as stated by (Allen et al., 1998b).

$E\ T\ o = 0.408\ \Delta \frac{(Rn-G)+\gamma\frac{90}{T+273}*U2(es-ea)}{\Delta+\gamma\ (\ 1 + 0.34\ u\ 2\ )})$--equation (3.12).

Where: R_n = net radiation (MJ/m²/day), G = soil heat flux density is mean air temperature (°C) , u 2 is wind speed at 2 m height (m/s) ,e s −e a is saturation vapour pressure deficit (kPa) Δ is slope of the vapour pressure curve γ = psychometric constant.

2. Crop Evapotranspiration (ETc:)Crop evapotranspiration (ETc) was calculated by multiplying reference evapotranspiration with the crop coefficient.

ETc = Kc×ETo--equation (3.13).

Where: ETc is crop evapotranspiration (mm/day),Kc is crop coefficient, ETo is reference evapotranspiration (mm/day).

3. Irrigation Water Requirement

The irrigation water requirement was calculated by subtracting effective rainfall from crop evapotranspiration.

IW = ETc−Pe --equation (3.14).

Where: IWR is irrigation water requirement (mm),ETc is crop evapotranspiration (mm),Pe is effective rainfall.

4. Gross Irrigation Requirement (GIR)

$GIR = \frac{NIR}{Ea}$ --equation (3.15).

Where: E a = irrigation application efficiency

5. Available Water Capacity (AWC)

$AWC = FC - PWP$---equation (3.16).

Where: FC is field capacity and PWP is permanent wilting point.

6. Root Zone Water Storage (S)

$S = AWC \times Z\,r$ --equation (3.17).

Where: Zr is rooting depth

7. Total Available Water (TAW)

TAW = 1000*(FC−PWP)*Zr ---equation (3.18).

Where: Zr = root zone depth (m)

8. Readily Available Water (RAW)

RAW = p*AW-- equation (3.19).

Where: p is depletion fraction to this research 50%.

3.4.1.4 Supply Adequacy Ratio (SAR)

The Supply Adequacy Ratio (SAR) serves as a crucial performance metric for assessing whether an irrigation system provides adequate water to fulfil crop water needs. It is defined as the ratio of the volume of water delivered to the demand for crop water, represented as a dimensionless figure (Molden et al., 1990). A SAR value of one signifies that the water supply completely meets crop requirements, while values below one indicate a shortfall in supply, potentially leading to crop water stress, diminished growth, and reduced yields (Bos et al., 2005). In contrast, SAR values exceeding one suggest over-irrigation, which may lead to inefficiencies such as deep percolation, nutrient leaching, and waterlogging (FAO, 1992).

In this research, SAR was determined by comparing the measured irrigation water supply, obtained through field discharge measurements utilizing the area–velocity method, with the estimated crop water requirement, which was calculated using CROPWAT integrated with CLIMWAT. These methodologies incorporated climatic data, crop characteristics, and soil properties(Allen, 2000).The analysis was performed across the head, middle, and tail sections of the irrigation system to capture spatial variations in water distribution. The findings were utilized to identify regions facing water deficits or surpluses and to evaluate the effectiveness and fairness of water allocation and management practices within the system (Bos et al., 2005).

The Karfe Small-Scale Irrigation (SSI) scheme receives water through a designed weir feeding two main canals that supply to 65 ha with designed discharge 94l/s for both MCs**.** river flows. The actual net flows delivered by the weir were measured using the area-velocity (floating) method (Equation 3.22), which accurately quantifies flow rates in open channels. These values were compared with the 4 months crop water requirements (CWR) for wheat (52ha), Cabbage (7ha) and potato (6ha) calculated using CROPWAT 8.0 with local meteorological data.

$$SAR = \frac{\text{Volume of water supplied}}{\text{Crop water requirement}}$$ ---equation (3.20).

3.4.1.2 Readily Supply Ratio (RSR)

The Readily Supply Ratio (RSR) was used to evaluate the adequacy of water delivery in the irrigation system. It is defined as the ratio of the actual discharge supplied to the required (design) discharge. The actual discharge (Qact) was assessed at both the right and left main canals utilizing the cross-sectional area and float method. The results were averaged over a four-month period (January–April) to reflect the irrigation season along the canal by sectioning of three plots head, middle and tail. This ratio was interpreted as that, an RSR of 1 signifies an adequate supply, an RSR greater than 1 indicates an over-supply, and an RSR less than 1 denotes an under-supply (Bos et al., 2005).

$$\text{RSR} = \frac{\text{Qactual}}{\text{Qreq along the canal}}$$ --equation (3.21).

<u>Remark:</u> The Readily Supply Ratio (RSR) assesses the sufficiency of water distribution at the canal (system level) whereas the Supply Adequacy Ratio (SAR) determines the supplied water fulfils the crop's water needs at the field level. This distinction positions RSR as a hydraulic indicator focused on the system, while SAR serves as a measure of adequacy based on crop requirements (Bos et al., 2005).

3.4.1.5 Reliability Index (RI)

The Reliability Index (RI) was employed to assess the consistency of water delivery within the irrigation system. It is defined as the ratio of the standard deviation of irrigation water supply to the mean supply, yielding a dimensionless measure of variability (Molden e, 1990). Lower RI values signify a more stable and reliable delivery system, while higher values indicate greater variability and reduced reliability. This unit is crucial as a consistent water supply mitigates the risk of crop water stress and supports optimal growth and yield. In this research, RI was computed using discharge measurements collected from the head, middle, and tail sections of the Karfe irrigation scheme throughout the irrigation season, capturing both temporal variations and spatial differences in water delivery. The findings offered insights into regions with inconsistent water supply and facilitated the evaluation of the overall effectiveness and management performance of the irrigation system (Bos et al., 2005; FAO, 1992).

$$RI = \frac{\text{Ns}}{\text{Nt}} * 100$$ --equation (3.22).

Where: RI is Reliability index, Ns is number of periods with adequate supply (RSR ≥ 1 & Nt is total number of periods /months.

3.4.1.6 Dependability Ratio (DR)

The Dependability Ratio (DR) was utilized to evaluate the reliability of the irrigation system in providing the essential water needed for crops. It was calculated as the ratio of the minimum recorded water supply to the crop water demand throughout the study duration. Values approaching 1 signify a very reliable system, whereas lower values indicate regular supply deficiencies (FAO, 1992; D. J. Molden & Gates, 1990).

$D\ R = \frac{Q\,min}{Q^{-}}$--equation (3.23).

Where: DR is Dependability ratio min is Minimum observed irrigation supply and Q^{-} is Average irrigation water supply.

3.4.1.7. Deficit Ratio (Dr)

The Deficit Ratio (Dr) was computed to assess the extent to which the irrigation system fails to meet the crop's water requirements. Data on soil moisture and canal discharge were utilized to calculate Dr for the head, middle, and tail sections. A Dr value of 0 signifies a complete water supply, whereas values exceeding 0 reflect a deficiency in water availability (FAO, 1992).

Dr = 1-SAR-- equation (3.24).

3.4.2 Performance Evaluation of the canal water delivery p system.

3.4.2.1 Performance Evaluation of the distribution system

The discharge throughout the canal was determined by integrating flow velocity with cross-sectional area measurements. Water velocity was gauged using the float method, where a plastic ball was set adrift along a 10 m segment of the canal. The duration (t) required to traverse this distance was recorded with a stopwatch. Surface velocity (Vs) was computed as: $Vs = \frac{L}{t}$, where L represents the distance covered by the float (m). To derive the mean channel velocity (V), a correction factor (k = 0.85) was applied: $V = 0.85 \times V\ s$.The cross-sectional area of the canal (A) was calculated using the measured flow depth (y) and the canal width (b = 0.4 m), which was determined with a staff gauge: A (m2) = $b \times y$.Then discharge of the canal (Q) was derived by: $Q = A \times V$, and During the measurement at the field three times repeated to take average and minimize errors. Following the determination of the total inflow (Qin) and total (Qout) of the canal system the following performance indicators were computed based on (Bos et al., 2005).

3.4.2.1The conveyance efficiency

Conveyance efficiency was used to assess the effectiveness of water transportation from the source to the field, pinpointing losses caused by seepage, leakage, and other external losses. The efficiency of conveyance (Ec) for the Karfe Small-Scale Irrigation Scheme (SSI) main canal was assessed using the area-velocity method, using rectangular cross section of the canal's dimensions. Materials and instruments used during this data collection were plastic ball (float marker for velocity) Stopwatch (timing) Staff gauge (flow depth measurement) Measuring tape (distance for float) Visual markers (for upstream and downstream locations).

$$Ec = \frac{Qin}{Qout} * 100 \quad \text{-------equation (3.25).}$$

3.4.2.2 Conveyance losses (CL)

Conveyance loss (CL) is the amount of irrigation water lost while being conveyed from the diversion weir through the canal system to the agricultural fields. These losses may result from seepage, evaporation, leakage, operational inefficiencies, livestock and household use, and unauthorized water abstractions. Conveyance loss is an important indicator of canal system performance and its effect on water availability within the command area. It was determined by measuring canal discharge at the head and downstream sections using the area–velocity method and calculating the difference in flow. Generally, conveyance losses below 25% indicate acceptable performance, whereas losses exceeding 35% reflect poor canal efficiency and the need for improvement(FAO, 1989;FAO, 2007).

Was used to denote the water lost during transportation from the source to the field, were computed in Percentage (CL %):

$$CL\% = \frac{Qin - Qout}{Qin} * 100 \quad \text{-------equation (3.26).}$$

Ec was used to assess the efficiency of water delivery to the field, whereas CL to quantify the water lost during the conveyance process, collectively reflecting canal performance and informing enhancements to the system. According to FAO (1989) and FAO (2007), an efficient irrigation system typically shows conveyance losses of less than 25%, whereas losses exceeding 35% indicate poor system performance and the need for rehabilitation and improved management. Furthermore, conveyance efficiency (Ec) is used to evaluate the effectiveness of water delivery to the field, while conveyance losses (CL) quantify the magnitude of water lost during transmission. Together, these indicators provide a comprehensive assessment of canal performance and support the identification of necessary system improvements, as noted by (Molden et al., 2001).

3.4.2.3 Distribution Uniformity (DU)

To assess the uniformity of irrigation water distribution within the farm field, soil samples were collected from three points at a depth of 0-90cm in each plot immediately after irrigation. The samples were weighed using a hand balance and then oven-dried at 105°C to determine the soil moisture content that stored in the soil after irrigation. Based on the moisture content obtained from nine sampling points across the three sections, the distribution uniformity (DU) of irrigation water was calculated using the low quarter method.

DU = $\frac{\bar{x}_{lq}}{\bar{x}}$ ×100--- equation (3.27).

Where: $\bar{X}_{lq}$ represents the average of the lowest quarter (25%) of soil moisture values and $\bar{X}$ is the overall average soil moisture. This was based on Jens B. Christiansen (1942), mostly used uniformity evaluation in surface irrigation system. *Producers*

1. List the moistures content values in ascending order
2. Select the lowest 25% of values

3. Calculate their average values and overall average

4. Compute the DU% by divided the average of 25% to total average and times by 100.

3.4.2.4. Equity Index (EI)

Equity of water distribution was defined as the degree of fairness in allocating irrigation water among different sections of the command area, namely the head, middle, and tail reaches. Evaluating equity was essential in irrigation performance studies, as it helps to identify whether all users receive a proportionate share of water, particularly in gravity-fed systems where head-end users often have an advantage (Bos et al., 2005).

In this study, equity was assessed using the volumetric method using the bucket at three off take torn out points of each three sections head, middle and tail using Christiane's coefficient of uniformity(CU) formula using flow amounts in each nine off take points and coefficient of variation (CV indicators to evaluate equity index. Then compares the actual flow delivered to each off takes with the average flow delivered across all sections. This approach is widely recommended for irrigation system evaluation due to its effectiveness in detecting spatial imbalances in water distribution (Bos et al., 2005). The equity index was computed using the following equation:

ER = (1- ($\frac{\sum_{i=1}^{n} Qi-Qavg)}{n*Qavg}$)*100--equation (3.28).

Where: EI is Equity index (dimensionless), Qi is flow delivered to the i^{th} section (L/s), Q_{avg} is average flow delivered across all sections (L/s), and n is number of sections. This method was provided a quantitative measure of fairness in water allocation and helped identify distribution inequalities, particularly the extent to which tail-end users were disadvantaged compared to head-end users, which is a common issue in surface irrigation systems (Moldenet al., 1990).

3.4.2.5 Coefficient of Variation (CV)

Coefficient of variation was used to indicate a considerable degree of variability in water distribution across the scheme. Higher CV values suggest that the flow distribution is inconsistent and used in equity index in order to compute distribution uniformity along the canal system to compare sections (head, middle, tail) using flow of nine off takes.

$$CV = \frac{\text{Standard Deviation of flows}}{\text{Mean Flow}}$$ --equation (3.29).

3.4.6. Delivery Performance Ratio (DPR)

This was applied to indicate how closely the actual delivered flows match the designed discharge of the canal system. Design Q is 94l/s of water.

$$DPR = \frac{\text{Qactual}}{\text{Qdesign}}$$ --equation (3.30).

3.4.3 Evaluation of Irrigation Structure Performance

The assessment of the structures within the Karfe Small-Scale Irrigation Scheme was carried out to evaluate their physical state, hydraulic functionality, operational effectiveness, and the overall dependability of the in structure. This assessment was systematically conducted starting from the diversion weir, followed by the intake head regulator, the main c

anals (both left and right), and the downstream hydraulic structures, adhering to the actual water flow direction of the irrigation system. The objective of this evaluation was to detect any structural degradation, hydraulic inefficiencies, operational constraints, and sedimentation issues that could hinder water conveyance and distribution throughout the scheme (FAO, 1996; Molden et al., 1990). Field data collection involved the use of measuring tapes to determine canal dimensions, staff gauges to assess water depth, cameras for photographic evidence, and float to measure flow velocity. Initially, full list of infrastructures were performed based on the design information, which included the diversion weir, head regulator, main canals, off-take structures, culverts, canal lining sections, and retaining walls in infrastructures: accessory roads, drainages silt escapes, flow measurements. Using the standard list table of the structure, during the observation recording all necessary information's about each system comments of the scheme. Additionally, structures that were part of the design but were either absent or collapsed were also recorded to assess the completeness of the infrastructure (Bos et al., 2005). Following this, physical condition inspections were conducted for each structure. These inspections concentrated on identifying structural cracks, erosion of canal banks and beds, sediment accumulation, seepage or leakage along the canal lining, vegetation growth within the canals, and damage resulting from livestock or human activities in the vicinity. Photographic documentation was captured to corroborate the field observations (FAO, 1992).

Hydraulic assessments were also performed at selected canal sections by measuring canal width, water depth, and flow velocity. Canal discharge was determined through the area–velocity method and subsequently compared with the design discharge to identify hydraulic discrepancies arising from slope irregularities, sedimentation, or structural damage(FAO, 1992;Molden et al., 1990). The operational performance was assessed by examining the functionality of gates, off-takes, and canal sections to ascertain whether the irrigation structures were capable of effectively regulating and conveying water to the command area. Structures that functioned as intended were categorized as functional, whereas those that were damaged or obstructed were noted as non-functional(FAO, 2012). Utilizing the gathered field data, various quantitative performance indicators were calculated to assess the performance of the irrigation infrastructure.

3.4.3.1 Structural Condition Index (SCI)

The structural condition of irrigation infrastructures was evaluated using the Structural Condition Index (SCI) method, which assesses the physical and functional status of key components within the irrigation scheme. The assessment was carried out through field observation, visual inspection, and expert judgment based on standard evaluation criteria.Each structure (e.g., diversion weir, canals, regulators, measuring structures, and hydraulic crossings) was evaluated using six parameters: structural integrity, hydraulic functionality, mechanical condition, maintenance status, sediment/vegetation control, and safety/access. Each parameter was rated on a scale of 1 to 5, where: Based on these findings, a five-point rating scale was employed (5, Excellent), (4, Good), (3, Fair), (2, Poor) and (1, Failed). The overall condition of the irrigation system was ascertained by computing the average score derived from all inspected structures (Bos et al., 2005; FAO, 1996).

$$SCI = \frac{\sum \text{Sturactures Scores}}{N} \text{--equation (3.31).}$$

Where: SCI = Structural Condition Index, ∑Structure Scores = total rating scores assigned to inspected structures N = number criteria per structures evaluated.

This method enables identification of structurally weak components and supports decision-making for maintenance and rehabilitation of irrigation systems.

3.4.3.2. Effectiveness of Infrastructure (EI)

The evaluation of irrigation infrastructure effectiveness aimed to ascertain the ratio of functional structures to the total number of installed structures. Functional structures were defined as those infrastructures that can execute their designated hydraulic functions without substantial damage or operational failures. The evaluation encompassed diversion weirs, head regulators, off-take structures, and culverts situated along both main and secondary canals. This indicator serves to highlight the necessity for repair or rehabilitation of irrigation infrastructure (FAO, 2012; Klozen et al., 1998).

$$EA = \frac{\text{Number of functional sturcturs}}{\text{Total number of instolled sturactures}} \text{-------equation (3.32).}$$

Where: EI is total number of installed structures and N is number of functional structures.

3.4.3.3. Hydraulic Compliance Index (HCI)

The Hydraulic Compliance Index was employed to assess the extent to which the measured hydraulic parameters of irrigation structures align with the original design specifications. The hydraulic parameters taken into account include weir length width, depth, canal width, water depth, and discharge capacity. This indicator is instrumental in identifying discrepancies arising from sedimentation, canal deformation, or improper construction practices (Bos et al., 2005).

$$HCI = \frac{\text{Measured Hydroulic paramter}}{\text{Design Hydroulic Paramater}} \text{-------equation (3.33).}$$

3.4.3.4. Sedimentation Severity Index (SSI)

Sedimentation poses a prevalent challenge in small-scale irrigation systems, leading to a notable decrease in the hydraulic capacity of canals and associated structures. The Sedimentation Severity Index was used to assess the degree of sediment accumulation impacting irrigation infrastructures and canals. Structures were estimated sediment-affected when significant deposition diminished the effective flow area or impeded water movement (Loucks et al., 2017).

$$SSI = \frac{\text{Number of Sediment Affected Sturactures}}{\text{Total nNnumber of sturactures}} \text{-------equation (3.34).}$$

3.4.3.5 Overall irrigation efficiency (Eo)

Overall irrigation efficiency is characterized as the ratio of the volume of water effectively utilized by crops to the total volume of water extracted from the source into the irrigation system. This metric reflects the cumulative impact of both conveyance and field application efficiencies from the canal head to the crop root zone. Its primary objective is to assess the overall effectiveness of an irrigation scheme, quantify total water losses within the system, and evaluate the efficiency of water usage for sustainable irrigation management Allen et al., 1998; Bos et al., 2005).

According to the guidelines set forth by FAO and IWMI, overall irrigation efficiency in surface irrigation systems is typically categorized as good when it exceeds 60%, moderate when it falls between 40% and 60%, and poor when it is below 40%, contingent upon the condition of the system and the management practices employed. The overall irrigation efficiency can be calculated using the following equations:

$Eo = Ec \times Ea$ --equation (3.35).

Where: Eo represents the overall irrigation efficiency (%), Ec denotes the conveyance efficiency (%), and Ea signifies the field (application) efficiency (%).

3.4.3.6 Analysis of Structural Deformation and Stability

This section presents the analysis of structural deformation and stability analysis of the head works especially at weir structure. The assessment includes evaluation of weir axis alignment, seepage conditions, hydraulic performance, and stability of the left retaining wall using geometric, hydraulic, and structural analysis approaches. To evaluate the safety and performance of the structure Computed parameters were compared with basic engineering principles and guidelines standards such as Kisan et al.(1989), for weir alignment, Khosla's Seepage Theory for seepage analysis and USBR guideline for hydraulic jump design and startling basin design, and IS & Karl Terzaghi principles for structural stability analysis.

The research employs a quantitative analytical methodology that integrates field data gathering, engineering calculations, and benchmarking against established design standards. The analysis was performed based on the subsequent components:

- ✓ Weir alignment and deformation analysis
- ✓ Seepage and floor length analysis
- ✓ Hydraulic jump and stilling basin performance
- ✓ Retaining wall stability analysis
- ✓ Comparative evaluation with standards and root cause identification

Data collection method

Geometric information was obtained through GPS survey to determine the coordinates of the weir crest and river cross-section, which were then converted in to UTM (Zone 37N, WGS84) for accurate spatial analysis. Hydraulic data, including discharge, upstream head, and pre- and post-jump flow depths, were collected from design documents and field observations. In addition, structural and geotechnical data such as retaining wall geometry, foundation conditions, and loading scenarios were gathered from design reports and field inspection, supported by observations of structural damage, scour, and deformation.

A.Weir Axis Alignment and Deformation Analysis

A hydraulic structure requires alignment to allow uniform flow distribution. Ideally, the weir crest should be perpendicular (90°) to the direction of river flow to minimize flow concentration and local scour, as recommended by IS 6966:1973. The alignment of the weir axis was determined using vector geometry:

V_{weir} = (E_{right}-E_{left}), (N_{right}-N_{left}) --equation (3.36).

Where: V_{weir} representing weir axis direction,(Eright − Eleft), is the variation in Easting (the east–west axis) and (Nright − Nleft) is the variation in Northing (the north–south axis).

The ideal axis vector (perpendicular to river flow) is derived from the river cross-section orientation. The deviation angle (θ) is calculated as:

$\theta = \arccos\left(\frac{Vweir * Videal}{|Vweir| * |Videal|}\right)$---equation (3.37).

Accepted criteria

During the evaluation of the weir axis alignment, the calculated value of devoted angle was compared with standard for design of proper recommendation. Proper alignment is essential to ensure uniform flow distribution and to minimize local scour and hydraulic inefficiencies. According to BIS (1973), the weir axis should be nearly perpendicular to the direction of flow, and only small deviations are acceptable.

Table 3.4: Acceptable Limits for Weir Axis Deviation Based on IS 6966:1973

Parameter	Acceptable Limit
Weir axis deviation (θ)	< 5° Acceptable
Weir axis deviation (θ)	≥5° not Acceptable

The GPS coordinates of the weir crest (left, centre, right) and the corresponding river channel points at the same cross-section were converted into the UTM coordinate system (Zone 37N, WGS84) for accurate spatial analysis.

B. Floor Length Adequacy (Khosla's Seepage Theory):This theory, is developed by Khosla (1954) used to determine the safe floor length of hydraulic structures founded on permeable soils. It ensures that the exit gradient at the downstream cut-off does not exceed a critical value (generally 1/5 to 1/6) in order to prevent piping and scour. The dimensionless parameter is expressed as:The dimensionless parameter exit gradient (GE) is calculated as:

$GE = \frac{H}{d\pi\sqrt{\lambda}}$ -- equation (3.38).

Where: d is depth of downstream cut-off (m), H is maximum static head (m) and λ is floor length factor (dimensionless).

From Khosla's curves, the coefficient α was determined and the required total floor length (L-required)(m) was computed as:

(L-required) = α×d --- equation (3.39).

Table 3.5: Design Criteria for Floor Length and Exit Gradient (Khosla et al., 1954)

Parameter	Acceptable Limit
Floor length	≥ Lrequired
Exit gradient (GE)	≤ 0.20

C. Hydraulic Jump and Stilling Basin Performance

The hydraulic jump was considered the primary energy dissipation mechanism downstream of the weir. Its stability was evaluated using the Froude number, as recommended by

(USBR,1987). For effective energy dissipation, a stable hydraulic jump condition was required, typically corresponding to a Froude number range of 4.5 to 9.0.

$Fr = \frac{q}{\sqrt{(g*D1^3)}}$-- equation (3.40).

Where: Fr is Froude number (dimensionless),q is discharge per unit width ($m^3/s/m$),g is acceleration due to gravity (9.81 m/s^2),D1 is pre-jump depth (m).For a stable jump (Fr > 4.5), the stilling basin length is:

Lbasin = 5*(D2−D1) --- equation (3.41).

Where D2 = post-jump depth (m). For Fr < 4.5, the basin length must be increased by 25% to account for oscillating jump behavior (USBR, 1987).

Table 3.6: Accepted standards to design Stilling Basin Performance

Froude Number Range	Jump Type	Acceptability
4.5 – 9.0	Stable jump	Acceptable
2.5 – 4.5	Oscillating jump	Requires longer basin
< 2.5	Oscillating jump	Unacceptable

D. Retaining Wall Stability Analysis (Limit Equilibrium)

Gravity retaining walls must satisfy three stability criteria which are resistance to sliding, resistance to overturning, and prevention of tensile stresses at the base based on (IS 7894, 1975; Terzaghi, 1943).The analysis was considers two loading conditions (i) Saturated backfill with earthquake, and (ii) dry backfill with earthquake. Those criteria were computed as:

Sliding Stability (FS) = $\frac{\mu * \Sigma V}{\Sigma H} \geq 1.5$-- equation (3.42).

Where: μ is coefficient of friction (0.40 for clay foundation), ΣV is sum of vertical forces (kN/m) and ΣH is sum of horizontal forces (kN/m)

Overturning Stability (FS) = $\frac{\Sigma M \text{ stabilizing}}{\Sigma M \text{ overturning}} \geq 2$--- equation (3.43).

Where: ΣMstabilizing and ΣMoverturning are moments about the toe (kN·m/m).

Base Stress (Tension Check)(Pmin) = $\frac{\Sigma V}{b}(1 - \frac{6e}{b}) \geq 0$------------------------------------ equation (3.44).

Where: b is base width (m), e is eccentricity equals to (b/2 − (ΣM/ΣV)) (m)

Table3.7: Accepted standards of Stability Criteria Evaluation for Gravity Retaining Wall

Parameter	Symbol	Acceptable Limit	Status
Factor of safety against sliding	FSsliding	≥ 1.5	Acceptable
Factor of safety against overturning	FSoverturning	≥ 2.0	Not acceptable
Minimum base stress	Pmin	≥ 0 kN/m²	Not acceptable

Source(Terzahi,1943; IS 7894 , 1975)

3.4.4 Farmers' Irrigation Scheduling and Water Management Practices

This study aimed to assess the irrigation scheduling practices of farmers, their decision-making regarding water allocation, and the management of water at the field level within the irrigation scheme. The objective was to analyses how the irrigation behaviour of farmers affects water use efficiency, the fairness of water distribution, and the overall effectiveness of the irrigation system(FAO, 2012; Garibaldi, 2012; Molden et al., 1998).A mixed-methods approach was employed to evaluate irrigation scheduling, water management, institutional performance, and related challenges. Quantitative data were collected through structured household questionnaires, while qualitative information was obtained from key informant interviews and field observations. The survey captured farmers' irrigation practices, water use behaviour, training, maintenance activities, and conflict experiences. Interviews with WUA representatives, irrigation experts, and local officials provided insights into water allocation, institutional roles, and management constraints. Quantitative data were analysed using descriptive statistics, whereas qualitative data were analysed thematically. The integration of both approaches enabled a comprehensive assessment of irrigation system performance, institutional effectiveness, and sustainability.

3.4.5 Formulating Mitigation Strategies

Mitigation strategies were developed to improve the overall performance and efficiency of the Karfe irrigation scheme based on integrated results from water supply adequacy, conveyance and distribution efficiency, structural condition, and irrigation scheduling practices. First, the main technical, operational, and managerial problems were identified from previous analyses, including inadequate water supply, low conveyance efficiency, unequal water distribution, deteriorated infrastructure, and poor irrigation scheduling. Second, the identified constraints were prioritized according to their impact on system performance, water distribution equity, and reliability, with emphasis on critical issues affecting hydraulic efficiency and structural stability. Third, relevant literature, design standards, and best practices from similar small-scale irrigation schemes were reviewed to identify suitable solutions. Fourth, mitigation options were developed, including rehabilitation of hydraulic structures, canal maintenance and delisting, improvement of water distribution practices, enhancement of irrigation scheduling, and strengthening of institutional capacity through training and farmer participation. Fifth, the proposed strategies were evaluated based on technical feasibility, cost-effectiveness, and expected performance improvement.

Finally, the most effective and practical measures were selected and formulated as recommendations aimed at improving water conveyance efficiency, ensuring equitable water distribution, strengthening structural reliability, and enhancing the overall sustainability of the Karfe irrigation scheme.

3.4.6 Sampling Methods

In order to evaluate the perceptions of farmers concerning the effectiveness of the irrigation scheme and its associated institutional factors, a random sampling technique was utilized. This approach guarantees that every farmer within the population has an equal opportunity to be chosen, thereby reducing bias in the survey findings. The sample size was calculated using the formula suggested by Yamane(1967), which offers a straightforward method for determining sample sizes for a finite population:

$$n = \frac{N}{N+1(e)^2} \quad \text{--equation (3.45).}$$

Where: n = sample size N = total population size e = desired level of precision In this research: Total number of farmers (N) = 162 Desired precision (e) = 10% (0.1) By substituting the values into the formula: $n = n = \frac{162}{162+1(0.1)^2} = 62$.Consequently, a sample of 62 farmers was randomly chosen from each (head, middle, and tail) sections of the command area to guarantee representation from all segments of the scheme.

3.4.7 Overall the scheme performance

The overall performance of the irrigation scheme was evaluated by integrating the results of key performance indicators, including water supply adequacy, conveyance efficiency, distribution uniformity, irrigation scheduling practices, and farmers' perceptions. The results were compared with established irrigation performance standards to determine the level of scheme performance. In addition, information obtained from field observations, key informant interviews, and focus group discussions was used to support and interpret the quantitative findings. This integrated assessment helped identify the major strengths, weaknesses, and operational challenges of the scheme and provided a basis for recommending improvement measures.

3.7 Conceptual framework

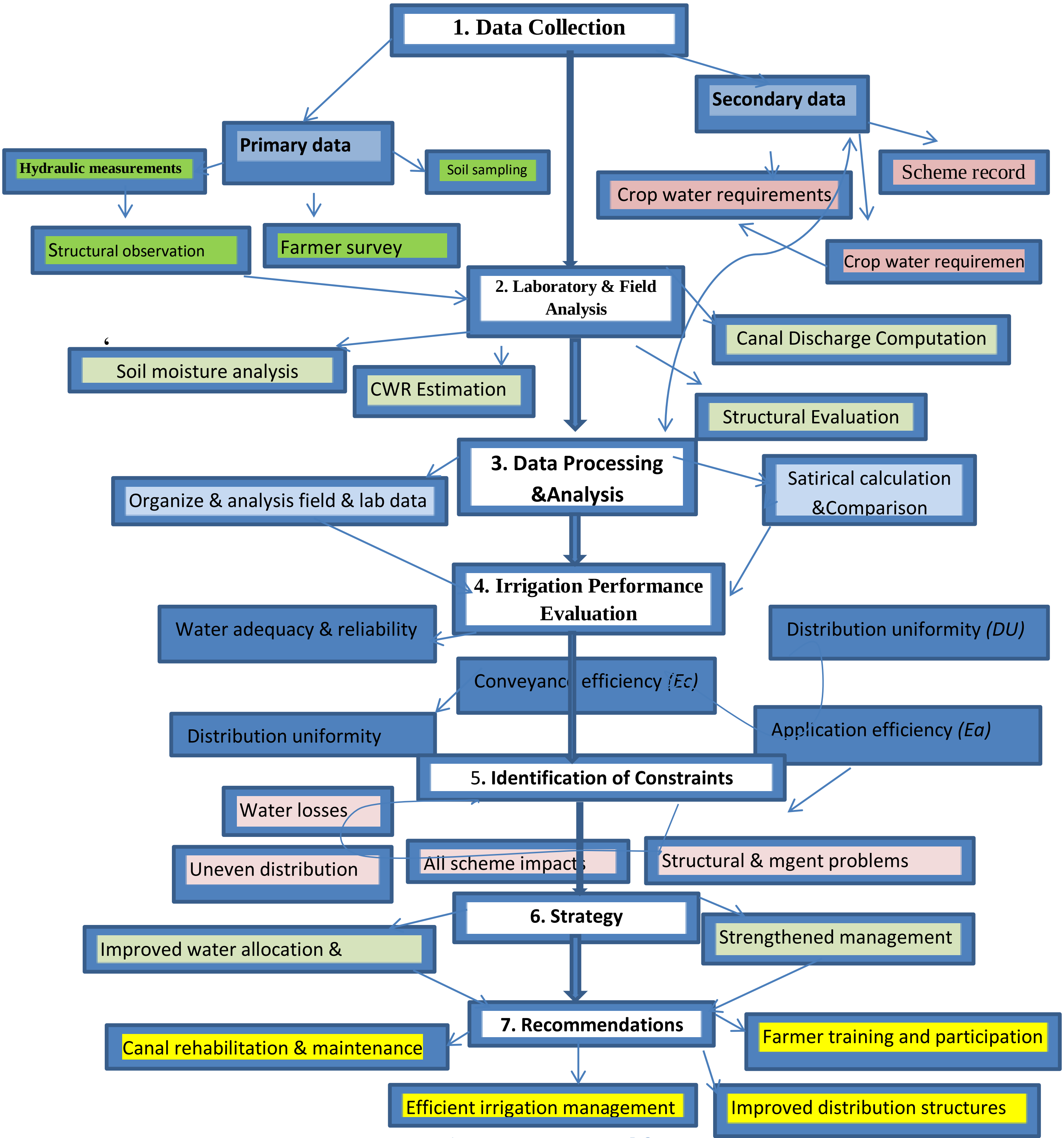


Figure7: Conceptual framework

4. Result and Discussion

This chapter provides a comprehensive overview of the empirical findings derived from the systematic performance assessment of the Karfe Small-Scale Irrigation Scheme (broad crested weir diverts water from Mojo natural river, 65 ha, lined Main canal length Right 2,230m with 500m unlined at the end &Left 1503m, surved 162 households) which was carried out throughout the entire most Wheat cropping season (January 07 - April 30, 2026). The results directly correspond to all five specific objectives done by dividing the scheme in to three section of study area in order to investigate the entire problems.

4.1 soil laboratory results and satirical analysis

This section provides a comprehensive overview of the laboratory and experimental findings derived from 45 soil samples that were systematically collected and analysed to define the physical characteristics of the soils and to calculate the moisture contents within the 3 ×depths (0-30, 30-60, 60-90 cm) × 3 sections (H, M, T) × 2 sampling events (before & after irrigation) and 3 ×depths (0-30, 30-60 , 60-90 cm) × 3 sections core sample for bulk density and for application efficiency (0-30,30-60,60-90cm) ×3 sections(H, M, T) and for DU%.3 ×points (0-90 cm)× 3 sections (Head, Middle, Tail).

4.1.1 Soil texture Characteristics

The soil Textural composition across the head, middle, and tail sections of the irrigation scheme is presented in Table 4.1Based on the soil texture triangle, soils with more than 40% clay content are classified as clay, which is consistent with the findings of this study. Such soils are known for their high water holding capacity, low permeability, and slow infiltration rates, which influence irrigation performance and water distribution along the scheme.

Table 4.1: Soil textural class of the karfe scheme

Section	Depth (cm)	%Sand	%Silt	%Clay	Textural Class
Head	0-30	18.36	28.42	53.22	Clay
	30-60	19.41	26.12	54.47	Clay
	60-90	18.11	25.38	56.51	Clay
Meddle	0-30	17.42	27.79	54.79	Clay
	30-60	17.54	26.21	56.25	Clay
	60-90	19.26	23.85	56.89	Clay
Tail	0-30	17.12	27.40	55.48	Clay
	30-60	18.15	24.99	56.86	Clay
	60-90	21.88	21.04	57.08	Clay
Average	0-90	18.69	25.91	55.39	Clay

The results indicate that the soil is predominantly clay across all sections and depths, with clay content ranging from 53.22% to 57.08%, silt from 21.04% to 27.79%, and sand from 17.12% to 21.88%. The average composition is 55.39% clay, 25.91% silt, and 18.69% sand.

When the result evaluated by based on soil triangle classification, more than 40% of clay percentage of soil texture is clay indicated as the result value of this study average value clay percentage of soil texture value 55.395 indicates that the Karfe irrigation soil texture clay.

All section soil texture nearly similar in spatial and although slight differences in sand and silt fractions may contribute to variations in infiltration and moisture retention observed in the result. This soil texture result was determined using the Soil Texture Triangle, hand-feel method, and field observation. The overall analysis indicated that the soil average consists of 55.39% clay, 25.91% silt, and 18.69% sand presents the vertisoil type. Based on the Soil Texture Triangle, this composition classifies the soil as clay. The high clay content contributes to strong aggregation, high water retention, and plasticity when wet.

4.1.2 Bulk Density Determination

Soil bulk density (ρb) was assessed at three different depths (0–30 cm, 30–60 cm, and 60–90 cm) throughout the head, middle, and tail sections of the Karfe irrigation scheme. The findings are compiled in Table 4.2.The recorded ρb values varied from 1.10 g/cm³ at 0–30 cm to 1.13 g/cm³ at 60–90 cm, resulting in an overall average of 1.11 g/cm³ across all sections.

4.1.3 Combined Soil Water Characteristics, Soil Moisture and Water Availability

The physical properties of the soil, such as bulk density (BD), field capacity (FC), permanent wilting point (PWP), available water content (AWC), total available water (TAW), and readily available water (RAW), were assessed in the head, middle, and tail sections at depths of 0–30, 30–60, and 60–90 cm. The findings indicate that the soils in all sections exhibit clay texture. The bulk density values were found to be between 1.10 and 1.13g/cm³ and the average is 1.11g/cm³.

Field capacity was observed to range from 0.37 and 0.41m³/m³, while the permanent wilting point was between 0.21 and 0.27m³/m³. The available water content (AWC) varied from 0.13 to 0.17m³/m³, with an average of 0.15m³/m³. Total available water (TAW) was recorded between 39 and 51 mm per layer (approximately 130 to 170 mm/m), whereas readily available water (RAW) ranged from 19.5 to 25.5 mm, with average values of 45 mm and 22.5 mm, respectively. The finding results of the soil properties are combined in table (4.3) below.

Table 4.3: Combined Soil Water Characteristics of Karfe irrigation scheme

Section	Depth (cm)	Textural Class	BD (g/cm³)	FC (m³/m³)	PWP (m³/m³)	AWC (m³/m³)	TAW (mm)	RAW (mm)
Head	0–30	Clay	1.11	0.40	0.26	0.14	42.00	21.00
	30–60	Clay	1.12	0.39	0.24	0.15	45.00	22.50
	60–90	Clay	1.13	0.38	0.21	0.17	51.00	25.50
Middle	0–30	Clay	1.10	0.41	0.27	0.14	42.00	21.00
	30–60	Clay	1.11	0.40	0.24	0.16	48.00	24.00
	60–90	Clay	1.12	0.38	0.22	0.16	48.00	24.00
Tail	0–30	Clay	1.10	0.40	0.27	0.13	39.00	19.50
	30–60	Clay	1.12	0.39	0.25	0.14	42.00	21.00
	60–90	Clay	1.12	0.37	0.21	0.16	48.00	24.00
Average	**0–90**	**Clay**	**1.11**	**0.39**	**0.24**	**0.15**	**45.00**	**22.50**

The result in the above table (4.3) indicated that the soils are classified as clay (Vertisol-type), noted for their significant water retention capabilities and limited infiltration rates.

The bulk density measurements (1.10–1.13 g/cm³) are consistent with the standard range for fine-textured soils (1.0–1.5 g/cm³) as reported by the (FAO, 2006) . The field capacity (FC) ranges between 0.37 and 0.41m³/m³, whereas the permanent wilting point (PWP) ranges from 0.21- 0.27m³/m³. These measurements align with the ranges reported by the FAO for clay soils, where FC generally varies from 0.36 - 0.45 m³/m³ and PWP from 0.20- 0.27 m³/m³(Allen et al., 1998) in FAO irrigation and drainage page-56. The available water content (AWC), determined as the difference between FC and PWP, ranged from 0.13 - 0.17 m³/m³, indicating that only a moderate portion of the stored water is accessible for plant utilization.

Consequently, the total available water (TAW) in the root zone was 130–170 mm/m, which falls within the FAO range of 120–200 mm/m for clay soils. These results are consistent with findings by Gensa et al. (2024), in the Woybo irrigation scheme, Southern Ethiopia, who reported field capacity values of 33.5–41.24%, permanent wilting point values of 21.9–27.2%, and total available water ranging from 101.5 to 163 mm/m for similar clay soils. The slight increase in bulk density with depth indicates subsoil compaction, which may hinder root penetration and decrease water movement. The variation in readily available water (RAW), which ranged from 19.5 to 25.5 mm, highlights the necessity for careful irrigation scheduling to fulfil crop water demands without causing stress.

4.1.4 Application Efficiency (Ea) & Storage Efficiency (Es)

The efficiency of the irrigation system (Ea) was assessed across the head, middle, and tail sections of the command area. The findings are presented in Table 4.4. The computed efficiencies were 49.65% for the head, 53.81% for the middle, and 62.42% for the tail, resulting in a field average of 54.82%. The depths of applied water were greatest at the head (357.92 mm) and marginally lower at the middle and tail (280.97 mm and 280.69 mm, respectively).

Table 4.4: Application Efficiency (Ea) & Storage Efficiency (Es) for Karfe SSI scheme

Section	Applied depth (mm)	Net Storage (mm)	Ea (%)	Dreq (mm)	Es (%)
Head	357.92	177.7	49.65	210.33	84.49
Middle	280.97	151.2	53.81	176.74	85.55
Tail	280.69	175.2	62.42	180.15	97.25
Average	**306.53**	**168.03**	**54.82**	**189.07**	**89.1**

The efficiency of application varies due to the influence of clay soils and differences in slope, the head section (49.65%) indicated low efficiency as a result of gentle steep slopes with runoff, faster water movement, less infiltration and excessive irrigation, while the middle section (53.81%) indicates nearly flat slopes with moderate runoff and infiltration efficiency. In contrast, the tail section (62.42%) attained the highest efficiency due to its flat level land less runoff, more opportunity for water to infiltrate into the root zone. Based on commonly used FAO guidelines for irrigation performance evaluation (FAO, 1997),recommendation, if Ea is 60 and greater than 70% “Excellent”, 60-70% is “good”, 50-60 “moderate” and less than 50% is “poor”. Based on this, the head section is poor, middle is moderate and the tail is good. The overall field average Ea (54.82%) is in the range of 50-60% so it is moderate, and this result is corresponds with the findings of (Mekonnen et al., 2018), who reported efficiencies of 46.3%, 65.9%, and 76.1% for the head, middle, and tail sections, respectively. The average for the total field, recorded at 54.82%, falls moderate within the standard ranges for surface irrigation. However, enhancing water management**,** optimizing irrigation schedules, and increasing farmer awareness could further improve efficiency.

4.1.5 Storage Efficiency (Es)

Storage efficiency was assessed using soil moisture measurements taken before and after irrigation in fields supplied with measured discharge. The net storage depth was estimated from the change in soil moisture and compared with the required depth (Dreq).Storage efficiency (Es) is commonly classified in irrigation performance studies, as the Es values greater than or equal to 90% indicates “good”, from 70-90% indicates “moderate “ and less than 70% value represents “poor” performance.

The result indicated in the above table 4.4 with application efficiency shown as: at the head section has a storage efficiency of 84.49%, indicating moderate performance, due to gentle slope 2-5% excess application, poor control and runoff losses. The middle section shows a slightly improved slightly improved efficiency of 85.55% because it has nearly flat slope 1-2%slope, but still reflects some inefficiency in water application. The tail section has the highest storage efficiency of 97.25% indicates good storage performance, suggesting more effective use of the applied water due to perfectly flat field levelling condition.

The overall field average storage efficiency is 89.10%, indicating generally moderate irrigation performance. However, the variation between head, middle, and tail sections suggests inequity in water distribution and differences in irrigation practices. Improving water control and adopting better irrigation scheduling, particularly in the upstream sections, can enhance overall efficiency and reduce water losses. These results agree with Molden (1997), which indicate that storage efficiency improves as field slope decreases and land levelling becomes more uniform, while poor control and gentle slopes increase runoff and application losses.

4.2 Water Supply Adequacy and Reliability

4.2.1 Supply Adequacy Ratio (SAR)

The adequacy of water distribution within the Karfe Small-Scale Irrigation (SSI) scheme was evaluated using the Supply Adequacy Ratio (SAR), defined as the ratio of actual water delivered (Qact) to crop water requirement (Qreq). Crop water requirements (CWR) for wheat (52 ha), cabbage (7 ha), and potato (6 ha) were considered through their different crop water requirements (CWR), crop coefficients (Kc), growth stages, and irrigation schedules using CROPWAT 8.0 based on local meteorological data, as described in Section 3.4.1.3. A SAR value of 1.0 indicates adequate supply, values greater than 1.0 indicate over-supply, and values less than 1.0 indicate under-supply(Allen et al., 1998).The Supply Adequacy Ratio (SAR), articulated as SAR (Qact/Qreq), served as unit less indicator of water delivery sufficiency. A SAR value of 1.0 signifies that the water supply satisfies crop needs, values exceeding 1.0 denote over-supply, while values below 1.0 reflect under-supply (FAO, 1998).

Table 4.5: Adequacy of water delivery performance of the Karfe SSI scheme

Location	Off-takes	Jan Qact/Qreq	Feb Qact/Qreq	Mar Qact/Qreq	Apr Qact/Qreq	Mean
Head	TO1	1.26	1.12	1.07	1.25	1.17
	TO2	1.30	1.17	1.14	1.33	1.23
	TO3	1.27	1.11	1.16	1.30	1.21
	Mean	1.27	1.13	1.13	1.29	1.21
Middle	TO1	1.13	1.03	1.03	1.15	1.09
	TO2	1.16	1.10	1.00	1.13	1.10
	TO3	1.13	1.04	1.08	1.12	1.09
	Mean	1.14	1.06	1.04	1.13	1.09
Tail	TO1	1.11	0.78	0.71	1.14	0.93
	TO2	1.18	0.76	0.79	1.11	0.96
	TO3	1.16	0.74	0.61	1.10	0.91
	Mean	1.15	0.76	0.70	1.12	0.93
	Spatial mean	1.19	0.98	0.95	1.18	1.08

From the result table 4.5, findings indicated both spatial and temporal fluctuations in water adequacy throughout the irrigation system that: the head section consistently received water above crop requirements, with SAR values ranging from 1.07 - 1.30 with mean of 1.21 hence over-supply was highest in January and April, the middle section received slightly above or near adequate water SAR 1.00- 1.16 with average value of 1.09 and the tail section SAR range 0.61- 1.18 with mean of 0.93, indicates water shortage during February and March mean (0.70–0.76) and adequate supply in January and April mean(1.15,1.12) .The spatial mean across the scheme was 1.08, suggesting slight over-supply overall, but with inequity along the canal from head to tail. A similar result was reported by (Efriem Mekonen &Tadesse (2017), who found adequacy values of 0.84, 0.63, and 0.85 for the head, middle, and tail reaches, respectively, indicating a decline in water supply toward the downstream areas and Alefu et al.(2023) observed similar patterns.

The general result indicates that: Excessive supply at the head led to waterlogging and inefficiency, attributed to early access and inadequate flow regulation Zinabie Mekonnen (2018). The middle section Experienced a moderate supply with slight variations, whereas the tail section was under-supplied, indicates a risk of crop stress. These inconsistencies associated with inflow shortages, conveyance losses, slope, and irrigation scheduling (FAO, 1998), underscoring the necessity for improved flow management, fair distribution, and farmer education.

4.2.2 The Readily Supply Ratio (RSR)

The Readily Supply Ratio (RSR), which is defined as the ratio of actual water delivered to the crop water requirement (Qact/Qreq), was utilized to assess the timeliness and sufficiency of irrigation water supply within the scheme system. As stated by the FAO (1998),RSR values are categorized as; ≥1.0 (excellent), 0.8–1.0 (good) and 0.6–0.8 (poor).The RSR was calculate using the equation (3.23) as indicated the following table (4.6).

Table4.6: Readily Supply Ratio of the Karfe SSI Scheme

Section	January	February	March	April	
	Qact/Qreq	Qact/Qreq	Qact/Qreq	Qact/Qreq	Spatial Mean
Head	20.58	4.66	4.40	16.05	11.42
Middle	5.78	1.32	1.24	4.35	3.17
Tail	3.29	0.77	0.71	2.57	1.83
Average	9.88	2.25	2.12	7.66	5.48

From the above result table (4.6): the Readily Supply Ratio (RSR) showed the spatial variation along the Karfe SSI canal system from head to tail. The head middle mean RSR value ranges from 4.4-20.58 ith mean 11.42, middle ranges from 1.24-5.78 with mean value of 3.17 and tail RSR ranges from 0.71-3.29 with mean value of 1.83.Based On the standard stated by FAO, head and middle sections were excellent (SAR ≥1.0) and tail was poor (SAR=0.6-0.8) due to February and March SAR (0.77 and 0.71), this was because of flow decreasing from the main source of the Mojo river during the season. These patterns correspond with the main conclusions of (Molden et al., 1998), who typically obtain water preferably and in larger observed that upstream users in surface irrigation systems volumes, whereas downstream areas frequently experience shortages as a result of conveyance losses, variations in slope, and inadequate flow regulation. These variations are influenced by conveyance losses, canal slope, and inadequate irrigation scheduling (Allen et al., 1998). Therefore, improving flow control structures, promoting equitable water distribution, and enhancing farmer awareness of irrigation scheduling are essential to optimize system performance.

4.2.3 Reliability Index (RI)

The Reliability Index (RI) serves as a crucial measure of irrigation efficiency, indicating the percentage of the number of periods with adequate supply (Ns)(SAR values greater or equal to 1) to the total number of periods (Nt= four months)the needs of crops (FAO, 1992;Molden, 1997). The RI was determined for the head, middle, and tail sections using the equation (3.25) and the result written in the table (4.8).

Table 4.7: Reliability index of the Karfe Irrigation Scheme

Section	Ns	Nt	Reliability Index (%)
Head	4.00	4.00	100.00
Middle	4.00	4.00	100.00
Tail	2.00	4.00	50.00

The result on the above table (4.7) indicated that: the head and middle parts of the Karfe irrigation scheme showed complete reliability (100%), consistently fulfilling crop water needs. Conversely, the tail section shows a reduced reliability index (RI) of 50%, reflecting periodic water shortages.

4.2.4 Relative Water Supply (RWS)

The adequacy of irrigation water supply was evaluated using the Relative Water Supply (RWS), defined as the ratio of available water supply to crop water requirement. This indicator assesses the ability of the irrigation system to meet crop water demand along different canal sections under varying flow conditions. According to Molden et al.(1998), RWS, value greater than 1.0 indicates adequate and reliable supply, values between 0.8 and 1.0 indicate moderate performance, while values less than 0.8 indicate inadequate and unreliable water delivery.

Table4.8: Relative Water Supply by Canal Section of the scheme

Section	Qavailable (lowest RSR)	Required (Qreq=1)	Dependability Ratio
Head	4.40	1.00	4.40
Middle	1.24	1.00	1.24
Tail	0.71	1.00	0.71

From the above result the head section relative water supply RWS value 4.40 in the range of sufficient and reliable supply, exceeds the minimum water requirement by more than four times, middle Section RWS Value of 1.24 in the range value of sufficient and reliable water supply with exceeds the moderate requirement indicates random minor shortages during extreme conditions and tail Section with RWS of

0.71in the range of less than 0.8 reflect inadequate and unreliable water delivery, fulfils the minimum requirement in only 71% of the reference events, which signifies low reliability indicates Water shortages probable, during dry periods.

This distribution pattern reflects the typical upstream–downstream inequity observed in gravity-fed irrigation systems, where upstream users tend to receive excess water due to priority access and lower conveyance losses, while downstream users experience shortages as a result of cumulative conveyance losses, upstream abstractions, and operational inefficiencies. Similar findings have been reported in irrigation performance evaluations by (Abo et al., 2024).

4.3 Evaluation of the delivery Performance of the canal system

To address the second specific objective, the irrigation system's performance was assessed in terms of water conveyance and distribution uniformity. The analysis examined how effectively water was delivered along the canal and how evenly it was distributed across the head, middle, and tail sections of the command area. Key performance indicators, including conveyance efficiency (Ec), conveyance losses (CL), coefficient of variation (CV), equity index (EI), and delivery performance ratio (DPR), were employed for evaluation (IWMI, 1998).

The results showed spatial variations in water delivery and distribution efficiency, primarily influenced by canal topography, field slope, operational practices, and canal conditions. These findings provide a quantitative foundation for evaluating the system's efficiency, equity, and uniformity and highlight critical areas for improving water management.

4.3.1 The conveyance efficiency

Conveyance efficiency (Ec) was calculated as the proportion of water reaching downstream sections relative to the total volume diverted at the canal head. This was computed by combined the left and the right Ec and compute losses after computing separately within their MC in section using their distance for right MC length of 2810m(2.81km) and the left MC2 length of 1500m(1.5km) as indicated in the table 4.9 below.

According to the FAO (1998) and the IWMI (2007), conveyance efficiency (Ec) greater than 85% is considered good performance, while values between 75% and 85% indicate moderate performance, and values below 70% represent poor performance. Similarly, conveyance losses of less than 10% are considered good, losses between 20% and 30% indicate moderate (fair) performance, and losses greater than 25% are classified as poor performance.

Table 4.9: Conveyance efficiency and Conveyance Loss of the Karfe SSI scheme

Section	MC length(m)	Qin(l/s)	Qout (l/s)	conveyance efficiency(Ec) %	Loss (CL) %
Head	500/940	69	63.75	92.39	7.61
Middle	1000/1870	63.75	58.75	92.16	7.84
Tail	1500/2810	57.75	52.5	90.91	9.09
Overall field	0–1500/0-2810	69	52.5	76.09	23.91

From the results presented in table above 4.9 observed that the conveyance efficiency (Ec) at head section is 92.39%, at middle section is 92.16%, tail section 90.09%,and while the overall system efficiency is 76.09. According to the FAO(1998) and IWMI (2007),commonly used standards the head, middle and tail section conveyance performance efficiency is greater than 85% fall within the good performance range. However, the overall system performance efficiency (76.09%) falls under moderate performance range (75-85%).The observed conveyance efficiency (Ec) along the Main Canals (MCs) shown a gradual decline from the head to the tail, recording values of 92.39 % at the head, 92.16 % in the middle, and 90.91 % at the tail, culminating in an overall efficiency of 76.09 % for the entire canal system. This pattern indicates the cumulative impact of seepage sediments accumulation and slight operational inefficiencies, external losses and impact of unlined present along the in the right main canal.

These results align with Ashine et al.(2025), reported the Ec at head ,middle and tail values (87.73%, 72.86%, 69.40%) respectively and overall Ec value was as 76.44% for the scheme entire system ,which indicate that unlined or inadequately managed canal segments reduce overall conveyance efficiency of Dabasso Lamaffa Small-Scale Irrigation (SSI) scheme.

4.3.2 Conveyance losses (CL)

Conveyance losses (CL) represent the difference between the water diverted at the canal head and the flow actually delivered downstream by computing the result using equation (3.32), indicated in the table (4.11) above with Ec. According to the results presented in Table 4.11, the conveyance loss (CL) verified at the head was 7.61 %, at the middle 7.84 %, and at the tail 9.09 %, concluding in an overall system loss of 23.91 %. As per the standards set by (Allen et al., 1998) and (IWMI, 2007), losses that are below 10 % in the head, middle, and tail sections are good acceptable, whereas an overall system loss ranging from 20–25 % signifies moderate performance.

The CL observed along the Main Canals (MCs) showed a gradual increase from the head to the tail, indicative of cumulative seepage, minor operational inefficiencies, and the effects of unlined canal sections along the right main canal. These findings align with the research conducted by (Ashine et al., 2025) which reported an increase in CL from 12.27 % at the head, 27.14 % at the middle, and 30.60 % at the tail, resulting in an overall system loss of 23.56 % for Dabasso Lamaffa Small-Scale Irrigation (SSI) scheme..

4.3.3 Distribution Uniformity (DU)

Distribution Uniformity (DU, %) was evaluated to assess the uniformity of irrigation water application across the field under surface (furrow) irrigation. The DU values were computed using soil moisture measurements taken from the head, middle, and tail sections fields at depth of 0–90 cm after irrigation, in order to determine how uniformly water was stored within the crop root zone, using Equation (3.28). Based on these measurements, the average DU values are presented in Table 4.12.The average distribution uniformity of water application in the field at three sections.

For surface irrigation systems, DU is commonly evaluated using the low-quarter distribution uniformity (DU_{lq}). Based on FAO (1989),commonly used guidelines and Burt et al.(1997),standard states that DU values are classified as follows: DU ≥ 85% indicates excellent uniformity, DU between 70% and 85% indicates good or acceptable uniformity, DU between 60% and 70% indicates fair or moderate uniformity, and DU < 60% indicates poor uniformity.

Table 4.10: Field Distribution Uniformity (DU) Based on Soil Moisture Measurements

Location	Average Depth(mm)	Min. Depth(mm)	DU (%)
Head	32.26	22.91	71
Middle	30.66	22.60	74
Tail	26.50	21.38	81
Field Avg.			**75**

The result presented in the table 4.10, indicated that at the distribution uniformity (DU) at head, middle and tail section are 71%, 74%, and 81% respectively with overall average DU% of 75%. According to most commonly used in surface irrigation scheme performance evaluation guide line of FAO (1998),DU values greater than 85% is classified as excellent, values from 70-85% as good, value from 60-70% as moderate, and less than 60% as poor distribution uniformity.

The results presented in Table 4.10 indicate that the distribution uniformity (DU%) at the head, middle, and tail sections are 71%, 74%, and 81%, respectively, with an overall average DU of 75%. According to FAO (1998) guideline for surface irrigation performance, DU values greater than 85% are classified as excellent, values between 70% and 85% as good, values between 60% and 70% as moderate, and values less than 60% as poor.

Based on these criteria, the DU values obtained for the head, middle, and tail sections (71%, 74%, and 81%) fall within the good performance category. The lowest DU was observed at the head section (71%), while the highest value was recorded at the tail section (81%). This variation suggests that the tail section receives relatively more uniform water distribution compared to the head. The observed differences can be attributed to field topography, where the head section is relatively steeper, the middle section has moderate slope, and the tail section is comparatively flat, facilitating more uniform water distribution.

This result is consistent with Zinabie (2018), who, in a study conducted at the Golina small-scale irrigation scheme, reported significant spatial variability in irrigation water distribution, where application efficiency ranged from about 46% at the head reach to 76% at the tail reach. This variation indicates non-uniform water application across the field and reflects overall poor irrigation performance.

Therefore, although the overall distribution uniformity is within the acceptable good range, improvements in water management practices such as proper land levelling, controlled flow distribution, and optimized irrigation scheduling are necessary to further enhance uniformity and overall irrigation efficiency.

4.3.4. Equity Index (EI)

Equity Index in irrigation refers to the fairness in water allocation among users. It is often evaluated by comparing flows at different locations (head, middle, tail).The volumetric method is one of the simplest and most widely used techniques for measuring discharge in small irrigation systems. It involves collecting a known volume of water and recording the time required to fill the container. Based on this to check equity along plots discharge was then calculated as volume over time (l/s), using the bucket-stopwatch method by repeated three times in order to decrease error. This method was selected due to the hydraulic flume were not available due to cost.

This method was provided a quantitative measure of fairness in water allocation and helped identify distribution inequalities, particularly the extent to which tail-end users were disadvantaged compared to head-end users, which is a common issue in surface irrigation systems (Bos et al., 2005).

4.3.5.1 Coefficient of Variation (CV)

The Coefficient of Variation (CV) is defined as the ratio of standard division to average values of flows at canal off-takes. It is used to evaluate the consistency, uniformity and equity of water distribution along the canal system. The CV values were computed using equation (3.32) based on the flow measurements at nine off takes. Based on FAO (1998) and Molden et al.(1998)), CV ≤ 0.10 is considered as "good", CV values from 0.10 - 0.20 indicated as "moderate" and CV>0.20 indicated as "poor" with high variability.

Table 4.11: Variability and Uniformity of Water Distribution along scheme canal

	CV%			
Month	Head	Middle	Tail	Avge CV
Jan	0.05	0.13	0.05	0.07
Feb	0.09	0.05	0.03	0.06
Mar	0.06	0.06	0.01	0.04
Apr	0.04	0.02	0.03	0.03
Average	0.06	0.06	0.03	0.05

The results in the table 4.11 indicated that, the head section CV ranges from 0.02 - 0.06 with the average value of 0.04, indicating good equality water distribution. Similarly the middle CV ranges from 0.02-0.06 with average value of 0.04, which reflects good equity. The tail CV value ranges from 0.05-0.18 with average value of CV 0.07 with high variability indicating relatively higher variability compared to the head and middle sections. This suggests that water distribution becomes less uniform towards the tail end of the canal system.The overall average CV for the canal system is 0.05, which is below the 0.1 threshold, indicating generally good equity along the canal.

The results is agreed with consistent with findings by Mekonnen et al.(2024), reported CV values of 0.03–0.06 of Shimburit Small-Scale Irrigation Scheme, indicating good water distribution

Table 4.12 Monthly Delivery Performance Ratio at each section of the Scheme

Section	January Qact/Qdesign	February Qact/Qdesign	March Qact/Qdesign	April Qact/Qdesign	Spatial Mean
Head	0.71	0.63	0.61	0.60	0.64
Middle	0.65	0.59	0.57	0.53	0.58
Tail	0.57	0.52	0.49	0.48	0.51
Average	0.64	0.58	0.55	0.54	0.58

The results presented in the above table 4.12 indicated that, as the delivery performance ratio (DPR) at the head, middle and tail sections ranged from 0.6-071, 0.53-065, 0.48-57 with average value 0.64, 0.58, 0.51 respectively. Monthly averages from January to April were 0.64, 0.58, 0.55, and 0.54.

The Qact/Qdesign ratio decreased from 0.64 in January to 0.54 in April, with an overall average of 0.58. This indicates that the irrigation scheme delivered only 58% of the design discharge, reflecting inadequate and unreliable water supply throughout the irrigation season. The declining trend suggests increasing water shortages, conveyance losses, and operational inefficiencies, which may negatively affect crop water requirements and overall scheme performance.

Spatially, DPR decreases from 0.64 at the head to 0.58 at the middle and 0.51 at the tail, indicating a progressive reduction in delivery efficiency along the canal and revealing inequity in water distribution, where downstream users receive less water. Temporally, DPR declines from 0.64 in January to 0.54 in April, suggesting a gradual reduction in water availability during the irrigation season.

According to IWMI (2007) and FAO (1989), DPR values greater or equal to 85 % indicate excellent performance, 75–85 % good, 50–75 % moderate, and below 50 % poor performance. Based on this classification, the head and middle sections fall within the moderate performance category and the tail section approaches the lower bound of moderate to poor performance. The overall spatial mean DPR of 0.58 (58%) indicates that the canal system delivers only about 58% of the designed discharge on average.

This finding is consistent with (Adane et al., 2020), who reported that the Ashar and Zuma-1 small-scale irrigation schemes in Ethiopia delivered only 56% and 58% of the designed water supply, respectively, indicating similar moderate to poor water delivery performance and inequity along canal systems.

4.3.7 Overall Irrigation Efficiency

The scheme shows moderate overall irrigation efficiency due to conveyance losses and inefficient field water application. According to FAO (1998), overall irrigation efficiency falls within the reasonable performance range, as efficiencies around 40% are considered acceptable, while 50–60% indicate good performance.. Based on commonly adopted interpretations in irrigation performance studies, efficiencies above 60% are often classified as good, 40–60% as moderate, and below 40% as poor, depending on system conditions. In this Study of the overall irrigation efficiency was computed by multiplying the application efficiency (Ea=54.82%) obtained from table (4.4) with the conveyance efficiency (Ec=76.09%) obtained from table (4.11), resulting in an overall irrigation efficiency (Eo) of 41.71%.

This result ranges in from 40-60%, the moderate performance efficiency, indicates that although the system is functional, a significant amount of water is lost before being effectively utilized by crops, therefore the scheme requires improvement in canal maintenance and on-farm water management practices.

This result is similar to with findings by Mekonen Tadess (1998) ,who reported as the overall irrigation scheme efficiency value 45% of the small scale irrigation scheme and the same Bos.M.g.et al (2005) Eo value was 50% indicates the overall efficiency ranges from 40-60% as moderate classification as this study result.

4.4. Evaluation of Irrigation scheme Structure Performance

This section presents the third specific objective of the study which means evaluation of the infrastructures performance. It assesses the condition and functionality of all over hydraulic performance of the system, through structural condition (SCI), infrastructure effectiveness (EI), and sedimentation severity (SSI) to evaluate its physical state, functionality, and sediment-related impacts and using engineering criteria's, including Khosla's and Terzaghi's principles, together with standard irrigation evaluation guidelines of FAO and IWMI. These are applied to identify the main structural and operational constraints affecting system efficiency and to determine the current performance status of the scheme.Overall, the results provide an integrated understanding of system performance, highlighting key limitations affecting efficiency, reliability, and long-term sustainability

4.4.1 Structural Condition Index (SCI)

The irrigation scheme's structural condition was assessed through the Structural Condition Index (SCI), which relies on six indicators: structural integrity, hydraulic functionality, mechanical condition, maintenance status, sediment/vegetation control, and safety/access. The SCI values calculated for each structure are shown in Table 4.12,for each parameter received a rating from 0 to 5, defined as follows:(5 = Excellent),(4 = Good),(3 = Fair),(2 = Poor),(1 = Failed) and (0 = not present).

Based on commonly used in performance evaluation guide lines for Bos et al. (2005) and the FAO (2012), the structural condition index(SCI) greater than 4.0 indicate good condition, values between 3.0 and 3.9 represent fair condition, values from 2.0 to 2.9 indicate poor condition, and values below 2.0 indicate failed condition.

Table 4.13: Structural Condition Index (SCI) Evaluation of Irrigation Scheme Components

Structure	No	Structural integrity	H.functionality	Mechanical condition	Maintenance status	Sediment control	Safety	Sum	SCI	Condition level
Diversion weir/Intake	1	4	4	3	3	2	3	19	3.17	Fair
Head Regulators	2	3	1	2	1	3	1	11	1.83	Failed
Retaining walls	2	2	2	2	2	3	1	12	2.00	poor
Division boxes/under sluice Regulators	4	3	2	3	1	1	1	11	1.83	failed
stilling basin	1	3	3	3	2	3	3	17	2.83	poor
Road & drainages	0	0	0	0	0	0	0	0	0.00	noone
Road Crossings/ Culverts	6	4	4	3	3	3	3	20	3.33	Fair
Main Canals	2	4	4	3	2	3	2	18	3.00	Fair
off-takes	more	3	3	2	2	1	1	12	2.00	poor
flumes	1	4	4	3	3	3	2	19	3.17	Fair
Field Channels	more	3	2	3	3	3	3	17	2.83	Poor
Overall average structural condition index(SCI)									**2.36**	Poor

As presented in Table 4.12, the Structural Condition Index (SCI) assessment shows that the irrigation scheme is in a generally poor structural condition, with SCI values ranging from 1.83 to 3.33 and an overall mean value of 2.36. This indicates that most of the irrigation infrastructure is functioning below acceptable performance levels and is affected by varying degrees of deterioration.

The results indicate that relatively better-performing structures include the diversion weir/intake, main canals, flumes, and road crossings/culverts, with SCI values between 3.00 and 3.33. These structures are classified as fair, meaning they are still operational and performing their intended hydraulic functions, although signs of wear and deterioration suggest the need for regular maintenance and preventive rehabilitation. Such as: Stilling basins, field channels, retaining wall and off-takes fall within the poor condition category, due to SCI values ranging from 2.00 to 2.83. These structures exhibit moderate structural deterioration and reduced hydraulic efficiency, largely due to insufficient maintenance and long-term wear, which negatively affects water conveyance and distribution reliability.

More critically, the head regulators and division boxes/under sluice regulators recorded the lowest SCI value of 1.83, placing them in the failed condition category. This indicates severe structural damage and malfunctioning, particularly in flow control and regulation functions, which significantly compromises the overall performance and operational reliability of the irrigation system.

Overall, the mean SCI value of 2.36 confirms that the irrigation scheme is in a poor structural state, with most components ranging from poor to fair condition. Although a few major hydraulic structures remain functional, the system is generally characterized by deterioration of control structures and inadequate maintenance practices.This result is agreed with Awulachew et al. (2011) who, reported that many irrigation schemes in Ethiopia are affected by deterioration of control structures and weak maintenance systems. Similarly, with Girma et al.(2007)who, reported that head regulators and distribution structures are among the most frequently failed components in small-scale irrigation schemes and further by FAO (2012) reported that average irrigation scheme condition in Ethiopia often falls around SCI 2.5, mainly due to aging infrastructure and sedimentation problems.

4.4.2 Effectiveness of Infrastructure (EI)

The effectiveness of irrigation infrastructure (EI) was assessed by examining the installation and operational capabilities of various system components. The table below explains the effectiveness of irrigation infrastructure (EI) classified by key system components, which included head works, conveyance, drainage, control structures, and access & safety structures, according to their installation and operational status. Based on common adapted in performance evaluation of Small scale irrigation schemes from guidelines of FAO (1996) and IWMI (2007),the effectiveness of infrastructure (EI) in small-scale irrigation systems is categorized as follows: values greater 70% indicates good performance, values ranging from 50% to 70% denote moderate performance, and values below 50% reflect poor performance.

Table 4.14: Infrastructure Effectiveness (EI) Across Irrigation System Components

Category	Total Designed	Actual Installed	Functional	Installation Rate (%)	Functional Rate (%)	EI (%)
head works (Weir(, Canal escape, Head regulator, Under sluice gate, Washing basin)	7	5	2	71.43	40.00	28.57
Conveyance (Main canal, Secondary canal, Tertiary canal, Drop structures, Flume, Aqueduct)	26	3	3	11.54	100.00	11.54
Drainage (Tertiary drain, Cross drainage)	9	5	5	55.56	100.00	55.56
Control structures (Off take gates, Division boxes/Regulators)	10	10	7	100.00	70.00	70.00
Access & Safety (Access road, Road crossing/Culvert, Foot bridge)	4	2	2	50.00	100.00	50.00
Overall	56	25	19	44.64	76.00	**33.93**

The results presented in Table 4.14 show that headwork structures including (weirs, canal escapes, head regulators, under sluice gates, and washing basins) exhibit a moderate installation rate of 71.43%, yet only 40% of these structures are functional, leading to a low overall EI of 28.57%, this value is below 50% reflects poor performance, This implies that while weirs, two head regulators, and two under sluice gates, structures have been built, but only the weir(1) and one side head regulator(1) were functional, and canal escapes (0) and washing basins (0) were uninstalled.

The conveyance system (comprising main canals, secondary canals, tertiary canals, drop structures, flumes, and aqueducts) has a very low installation rate of 11.54%, this value is below 50% reflects poor performance, but all installed components (left and right main canals(2) & flumes(1)) are functional with 100% functional rate and the flumes (EI) values of 11.54%. This minimum result is due to incomplete system development rather than functionality, those cases limited conveyance coverage severely obstructs water delivery efficiency to downstream users.

For drainage structures, the installation rate stands at 55.56%, this value is from 50% - 70% indicates moderate performance, with all installed structures fully functional (100% functional rate), resulting in an EI of 55.56%. This indicates a relatively better performance compared to other categories. But only tertiary drains &, Cross drainages built, However, along the main canals there were no any drainage structures, potentially heightening the risks of waterlogging and drainage issues during peak irrigation times and during rainy seasons.

The control structures, including off take gates and division boxes/regulators, exhibit the highest performance across all categories, achieving a 100% installation rate, a 70% functional rate, and an Efficiency Index (EI) of 70% this value is from 50% - 70% indicates moderate performance. This suggests that while all intended structures have been installed, some off take gates need maintenance to ensuring equitable water distribution, regulating flow and to control possess like leakage.

In contrast, access and safety structures, such as access roads, road crossings/culverts, and footbridges, have a moderate installation rate of 50%. However, all installed structures are fully functional, resulting in a 100% functional rate and an EI of 50% this value is from 50% - 70% indicates moderate performance. This indicates that left and right access roads were uninstalled, even though the existing (Culvert and Foot bridge) structures are in good condition and operational.

Overall, the irrigation scheme demonstrates an installation rate of 44.64%, a functional rate of 76.00%, and an overall effectiveness index (EI) of 33.93%. Based on commonly used evaluation methods derived from FAO (1996) and (IWMI (2007),this value (33.93%) is classified as poor, indicating that the irrigation scheme is underdeveloped and structurally incomplete, which significantly decrease its hydraulic performance and water distribution efficiency. These results suggest that enhancing irrigation performance necessitates not only the rehabilitation of existing structures but also the completion of missing components if possible.

This result is similar to Awulachew et al (2011),who reported that many Ethiopian irrigation schemes show reduced performance due to non-functional structures and poor maintenance. Similarly, by Bos et al. (1994),who stated that system effectiveness declines significantly when installed infrastructure is not properly maintained and operated

4.4.3 Sedimentation Severity Index (SSI)

The Sedimentation Severity Index (SSI) was used to assess the amount of sedimentation impact on the performance of irrigation infrastructure in the scheme. This was used to present the sediment deteriorated parts in quantitative severity weight based on numerical indicators mostly used irrigation evaluation guidelines (Bos et al., 2005) and (Molden et al., 1990), During this study the sediment effect level was classified in to four levels (severe, slight, low and none) and the severity weight were computed by measuring the current dimension to calculate the volume of the present condition and now the sediment volume equals designed volume mines current volume of the structure. The severity weight was computed as the ratio of sediment volume to total design volume times hundred.

$$\text{Severity weight (\%)} = \frac{(\text{Design storage volume} - \text{current storage volume})}{\text{Design storage volume}} * 100$$

Then weight affected amount for each was the product of each total time severity weight times hundred.

Based on this way the sediment evaluation was covered the main components as indicated in the table 4.15 with its corresponding affected weighted amount in the present as follows. The u/s of the weir total storage volume (887m3) obtained from design dimension and (673.83m3) sediment computed from 28m length of the weir up to the u/s length 40m.

$$\text{Severity weight Upstream of weir} = (\frac{887 - 673.83)}{887} * 100 = 24\%.$$

Tabl.4.15: Analysis of the Sedimentation Severity Index for Irrigation Structures of the scheme

No	Component	Total	Affected level	Severity weight	Weighted affected amount (%)
1	Upstream of weir	1	Slight	0.24	24.00
2	Head regulators	2	Low	0.1	20.00
3	Under sluice	2	Severe	1	200.00
4	stilling basin	1	Slight	0.15	15.00
5	Flume	1	None	0	0.00
6	Crossings/Culverts	2	None	0.13	26.00
7	Main canal in length (m)	4310	1100 m	0.25	6.38
Total structure		7		1.87	291.38
Total main canal length(m)		4310		0.25	6.38
SSI Structure					41.63
SSI Main canal					6.38
Overall average					48.01
SSI Combined average					24.00

The result presents in the table 4.15 indicates that the irrigation scheme is affected by sedimentation at a low to moderate level, with clear variation from 0 to 100% among components. Slight sediment deposition was observed at the upstream of the weir (24.00%) and stilling basin (15.00%), while the head regulators showed low sedimentation impact (20.00%). The under sluice exhibited the highest sedimentation severity with a weighted affected value of 200.00%, indicating severe sediment accumulation and poor flushing efficiency. In contrast, the flume showed no sedimentation impact, and crossings/culverts were only slightly affected (26.00%). For the main canal system, 1100 m of the total 4310 m canal length was affected by sediment deposition, resulting in an SSI value of 6.38%.The overall scheme sediment impact percentage is 48.01% .

Overall, the computed SSI Structure, SSI Main Canal, and Combined average of SSI values were 41.63%, 6.38%, and 24.00%, respectively, with overall total of 48.01% moderate sediment severity index values indicated that the irrigation system is generally functional but moderately affected by sedimentation, particularly at the under sluice structure fully closed by sediment due to this the two did not opened.

The sediment sources in the irrigation system were also strongly influenced by livestock activities. Livestock entering the canal system for drinking water contributed to sediment disturbance and increased turbidity. During crossing points, animals physically broke down soil aggregates along the canal banks through trampling, which led to the detachment of soil particles. These fine sediments were then transported into the main canal system, either directly through animal movement or indirectly through surface runoff after soil disturbance. This process significantly contributed to the overall sediment load entering the irrigation network and aggravated sedimentation problems within the canal system.

This result is agreed with Mekonnen et al.(2018), reported that in the Golina SSI scheme that 38.36% of irrigation structures were non-functional, mainly due to sedimentation, siltation of canals, and inadequate maintenance practices, leading to poor overall scheme performance. Similarly the most in the Upper Awash and Rift Valley irrigation schemes studies reported that sediment accumulation in canals and diversion structures frequently leads to reduced irrigation efficiency and increased maintenance demand, often exceeding 50% reduction in operational performance in poorly maintained schemes.

4.4.4 The Structural Deformation and Stability

4.4.4.1 Weir axis Alignment

To evaluate the alignment of the weir with the natural flow direction, UTM coordinates of the weir ends and river cross-section points were utilized to calculate orientation vectors and angles using the equation (3.44). Based on this the result is shown in the table (4.16).

Table4.16: Weir Axis Alignment and Deviation Analysis Indicators

Step	Description	Value
1	Weir left UTM coordinates	(487,195 m E, 940,512 m N)
2	Weir right UTM coordinates	(487,221 m E, 940,538 m N)
3	River left UTM coordinates	(487,215 m E, 940,514 m N)
4	River right UTM coordinates	(487,240 m E, 940,530 m N)
5	Compute weir orientation vector	(26, 26)
6	Compute river orientation vector	(25, 16)
7	Compute weir angle	45° from north
8	Compute river angle	57.4° from north
9	Compute deviation	57.4° − 45° = 12.4° (flow concentration)
10	Perpendicular requirement	Weir should be 90° to flow

The result in the table 4.16 show that: the weir axis orientation vector (Vweir) i= (26, 26) it cross ponds to an angle approximately 45° from north, while the river flow direction vector (Vriver=25, 16) corresponding to an angle of approximately 57.4° from north. The difference between the two vectors is 12.4° indicates the weir axis shifts by this angle, but the weir must be positioned at right angel (90°), in order to distributed flow load evenly along the weir section and reduce flow concentration and local scouring.

However at this study the angle deviation of 12.4° indicates the weir is not correctly aligned with the natural river cross-section by 90°. Based on IS 6966 (1973) statement of the standard limit of shifting about accepted weir axis less than 5°is tolerable but if greater than this it needs corrective measures are required, such as realignment of the weir axis or implementation of flow training works to minimize flow concentration and potential scour.

This indicates that the weir is not perfectly aligned with the natural flow direction of the river. Ideally, a weir should be oriented perpendicular to the dominant flow direction to ensure uniform hydraulic loading across the structure, reduce flow concentration, and minimize the risk of local scour near the abutments and apron.In summary as the result indicates weir axis alignment is missed due to this cause the weir is at risk in reality because the left retaining wall know failed 100%,towards the right side sediment accumulated and there is dawn stream scouring based on the observed information. So urgent measure must be taken to stabilize and protect the weir structure before further damage or complete failure occurs.

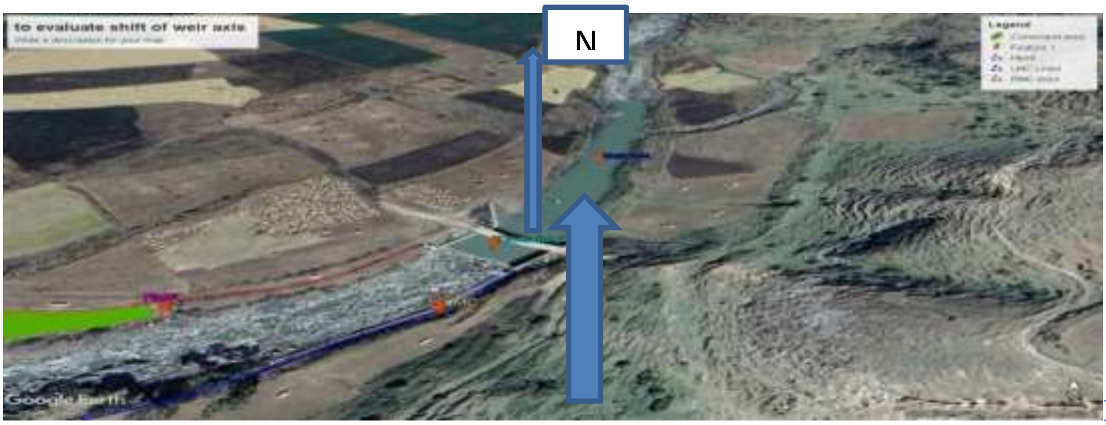


Figure 8: Location of the Karfe Weir Site

4.4.4.2 Floor Length Adequacy (Khosla's Analysis)

The floor length adequacy was evaluated using Khosla's Seepage Theory developed by (Khosla, 1954).The required floor length and exit gradient were computed using Equations (3.42)–(3.44). The computed values were then compared with standard hydraulic safety limits, while corresponding acceptance criteria's are summarized in Table 3.5. Based on this analysis, the detailed calculation procedures and obtained results are presented in Table 4.16 and 4.17.

Table 4.17: Assessment of Floor Length Sufficiency and Exit Gradient

Step	Description	Formulas	Value
1	Downstream cut-off depth (d)	-	3.00 m
2	Maximum static head (H)	-	4.20 m
3	Seepage factor(1/(π√λ))	$\frac{1}{\pi\sqrt{\lambda}} = \frac{d}{5H}$	3.00/(5×4.20) = 0.143
4	Khosla coefficient (α)	Obtained from Khosla curves	8.85
5	Required floor lengt(Lr)	Lr = α × d	8.85×3.00 =26.55 m
6	Design floor length (Ld)	-	25.00 m
7	Floor length deficiency (%ΔL)	ΔL= Lr-Ld	26.55−25.00=1.55 m
8	Percentage deficiency(%ΔL)	$\%\Delta L = \frac{\Delta L}{Lr} \times 100$	(1.55/26.55)×100% = 5.84% ≈ 6%
9	Exit gradient (GE)	$\frac{1}{d\pi\sqrt{\lambda}}$	0.143×4.2/3 = 0.2
10	Safety assessment	Comparison with permissible exit gradient	Slightly inadequate

Table 4.18: Summary of Floor Length Adequacy and Exit Gradient Analysis result

Parameter	Design Value	Required (Khosla)	Deviation	Standard	Status
D/s cut-off depth (d)	3.00 m	N/A	N/A	N/A	N/A
Maxi. static head (H)	4.20 m	N/A	N/A	N/A	N/A
1/(π√λ)	0.143	0.143	0	N/A	N/A
Khosla coefficient (α)	8.85	8.85	0	N/A	N/A
Floor length	25.00 m	26.55 mm	−1.55 (−6%)	≥ 26.55 m	Fail
Exit gradient (GE)	0.2	0.2	0	≤ 0.20	Borderline

- **Not applicable (N/A) presents no calculation is needed in that column for that parameter.**

The analysis of subsurface flow according to Khosla's theory reveals that most design parameters meet theoretical standards, with the exception of the floor length, which is slightly deficient. The downstream cut-off depth (d) is set at 3.00 m, deemed sufficient for managing piping and ensuring foundation integrity.

The maximum static head (H) on the structure is 4.20 m, which dictates the seepage conditions beneath the floor. The parameter value of 1/(π λ) is calculated as 0.143, aligning perfectly with the required Khosla value, thereby confirming the validity of the seepage correction assumptions.

Likewise, the Khosla coefficient (α) is 8.85, consistent with theoretical expectations, suggesting that the effects of floor geometry and cut-offs have been adequately addressed. Nonetheless, the calculated floor length is 25.00 m, whereas Khosla's criteria stipulate a required length of 26.55 m. This results in a shortfall of 1.55 m (approximately −6%), indicating a failure to meet the minimum safe length requirement. Consequently, the current floor design may be marginally insufficient in withstanding uplift pressures and managing seepage under extreme conditions. The exit gradient (GE) is determined to be 0.20, which matches the allowable limit (≤ 0.20). This suggests a borderline safe condition, where the structure is barely within the acceptable range against piping failure, necessitating careful attention to design safety.

This result is agreed with the reported by Kebede et al.(2021) investigated the Offiya irrigation diversion weir in Ethiopia and discovered that the exit gradient condition was on the verge of the permissible limit, primarily due to a lack of adequate seepage path length.

4.4.4.3 Hydraulic Jump and Stilling Basin Performance

The analysis of the hydraulic jump was performed according to the procedures specified in Table 4.17.The design flood discharge, the unit discharge and weir span from the design document, then the Froude number was derived using the pre-jump depth to assess the flow condition. After this, the post-jump depth was determined, and the required stilling basin length was estimated and modified based on the Froude number. Finally, the calculated length was compared with the given basin length to ensure its adequacy.

Table 4.19: Step-by-Step Procedure for Hydraulic Jump and Stilling Basin Design validation

Step	Description	formula	Value
1	Design flood discharge (Q)	From design	155 m^3/s
2	Weir span length (L)	From design	28 m
3	Discharge per unit width (q)	$Q = \frac{Q}{L}$	5.54 $m^3/s/m$
4	Pre-jump depth (D_1)	From design	0.59 m
5	Cube of Pre-jump Depth	D1^3	$0.59^3 = 0.205\ m^3$
6	Gravity Term	g*D1^3	9.81 × 0.205 = 2.01
7	Square Root Term	$\sqrt{(g \times D1^3)}$	√(9.11×2.05) = 1.42
8	Froude number (Fr)	$Fr = \frac{q}{\sqrt{(g \times D^3)}}$	5.54/1.42 = 3.90 = 3.93
9	Post-jump depth (D_2)	From design	3.02 m
10	Standard basin length (Ls)	Ls =5× (D2-D1)	5×(3.02−0.59)m=12.15 m
11	Corrected basin length (+25% for Fr<4.5)	Ld =1.25×Ls	1.25 × 12.15m = 15.19 m
12	Provided basin length(Lb)	Lb = 13 from design	13.00 m
13	Deficiency	Ld-Lb	15.19 − 13.00 = 2.19 m
14	Percent deficiency	$\% \text{ Deficiency} = \frac{Ld-Lb)}{Ld}*100$	$\frac{15.19-13)}{15.19} \times 100\% = 14.4\%$

The analysis of the hydraulic jump was conducted using USBR (1987) criteria to assess energy dissipation downstream of the weir. The calculated Froude number is Fr = 3.93, which is below the stable jump range of 4.5–9.0 and within the oscillating jump range (2.5–4.5), indicating an unstable flow condition.

According to standard hydraulic principles, the necessary stilling basin length for stable conditions is 12.15 m, which is marginally met by the available length of 13.00 m. However, given that the actual condition reflects an oscillating jump,(USBR, 2012) suggests a 25% increase in basin length, leading to a required length of 15.19 m.

The provided basin length falls short by 2.19 m (14.4%). This shortfall results in inadequate energy dissipation, causing an unstable oscillating hydraulic jump. As a result, there is a potential for residual turbulence and downstream scour, suggesting that the existing stilling basin design does not adequately meet USBR hydraulic safety standards under current flow conditions.

4.4.4.4 Retaining Wall Stability Analysis

The weir's stability was assessed under various loading conditions, taking into account both saturated and dry backfill states, with and without seismic loading. The analysis aimed to evaluate safety against sliding, overturning, and foundation bearing pressure, which are the primary failure modes for gravity hydraulic structures. Safety factors were compared to standard acceptable limits to determine overall structural stability.

Table 4.20: Retaining Wall Stability Results – Critical Foundation Section

Load Case	FSs	FSo	Pmin (t/m²)	FSs	FSo	Tension
Saturated backfill, no earthquake	2.28	3.07	0.05	Pass	Pass	No tension
Saturated backfill, with earthquake	1.45	1.88	−4.29	Fail	Fail	Tension
Dry backfill, no earthquake	2.32	3.59	1.84	Pass	Pass	No tension
Dry backfill, with earthquake	1.47	2.4	−0.07	Fail	Pass	Tension

The stability analysis indicates that the structure is secure under static conditions (both saturated and dry backfill), with safety factors for sliding and overturning exceeding the necessary thresholds and no tensile stress at the base, confirming stable foundation contact. However, during an earthquake, stability significantly declines.

For saturated backfill, the structure fails all criteria: sliding decreases from 2.28 to 1.45 (a 36% reduction), overturning falls below safe limits, and a negative base pressure (−4.29 t/m²) suggests tension and partial uplift, indicating total instability. In the case of dry backfill during an earthquake, the structure performs slightly better but remains critical. Sliding marginally fails (FS = 1.47 < 1.50), while overturning is still acceptable. A minor negative base pressure (−0.07 t/m²) indicates a partial loss of contact.

Observed Field Condition

Based on the observed condition and analysed results similarity the cause of failing retaining wall looks like due to seismic loading effect from earth pressure and earth quake forces indicates that it may be due to reduced sliding resistance and development of tensile stresses at the foundation. It suggests that the current design does not provide sufficient seismic safety margin and requires urgent strengthening or redesign measures such as increased base width, improved foundation treatment, or seismic-resistant structural modification.

Table 4.21: Summary of All Retaining Wall Sections

Wall Section	Critical Load Case	FSs	FSo	P_min (t/m²)	Overall Stability
Upper	Saturated + earthquake	1.89	Not reported	−0.82	Marginal
Middle	Saturated + earthquake	1.8	2.26	1.74	Marginal
Lower	Saturated + earthquake	1.45	1.88	−4.29	Collapsed

From the above summarized assessment result of the retaining wall sections with saturated backfill during an earthquake reveals differing performance levels throughout the structure's height. Based on (IS 7894, 1975) and (Terzaghi, 1963) about the standard values of factor of safety for sliding is (FS≥1.5) factor of safety for overturning is (≥2) and for base stresses (≥0) standards, the upper section has a sliding safety factor of 1.89, exceeding the minimum requirement, but negative base pressure (Pmin = −0.82 t/m²) indicates tensile stress and partial loss of foundation contact, rendering it marginally stable.

The middle section performs better, with sliding and overturning safety factors of 1.8 and 2.26, respectively, both acceptable. Positive base pressure (Pmin = 1.74 t/m²) confirms full foundation contact, yet its closeness to limits keeps it marginally stable under seismic conditions. Conversely, the lower section shows critical instability, with a sliding safety factor of 1.45 and overturning safety below acceptable levels (1.88). The significantly negative base pressure (Pmin = −4.29 t/m²) indicates severe tensile stress and uplift, confirming its failure under the loading condition.

The overall result indicates that: upper and middle are under marginal stable condition, however the lower section structurally unstable and has failed due to inadequate sliding resistance and high tensile stresses at the base. This indicates that the retaining wall is unsafe under saturated seismic conditions, with failure beginning in the lower section and potentially affecting the upper sections.

Table 4.22: Compliance with Standard Limits (Lower Section, Saturated + Earthquake)

Criterion	Standard (IS 7894/Terzaghi)	Actual Value	Deviation	Status
FS sliding	≥ 1.5	1.45	−3.3%	Fail
FS overturning	≥ 2.0	1.88	−6.0%	Fail
Base stress (tension)	Pmin ≥ 0	−4.29 t/m²	Tension	Fail

At the foundation level under saturated backfill with earthquake loading, the retaining wall fails all three stability criteria (IS 7894, 1975; Terzaghi, 1963). The factor of safety against sliding is 3.3% below the 1.5 requirement. The factor of safety against overturning is 6.0% below the 2.0 requirement. The base experiences tension of −4.29 t/m², indicating the wall lifts off its foundation. These numerical failures directly explain the observed total collapse of the left retaining wall.

4.4.4.5 Design vs. Actual vs. Standard

Table 4.23: Final Comparative Summary values of hydraulic and structure performance

Criterion	Designed values	Actual values	Standards	Status	effect
Exit gradient	Not computed	0.2	≤ 0.20	Borderline	Scour below cut-off
Froude number	3.93+	3.93	4.5 – 9.0	Fail	Weak hydraulic jump
Stilling basin length	13.00 m	13.00 m	≥15.19	Fail	Residual scour
FS sliding	1.45	1.45	≥1.5	Fail	Wall collapsed
FS overturning	1.88	1.88	≥2.0	Fail	Wall collapsed
Base tension	−4.29 t/m²	−4.29 t/m²	≥0 t/m²	Fail	Wall lifted off foundation

From the six key evaluated parameters fife fail and one is (exit gradient) at border to meet standard engineering requirements. The most critical failures are the weir alignment (12.4° deviation, 148% above tolerance), the stilling basin length (14.4% too short), and the retaining wall stability (FSsliding 3.3% below requirement, FSoverturning 6.0% below requirement, and base tension of −4.29 t/m²). These deficiencies collectively explain all observed field failures.The results indicate that the structure is hydraulically inefficient and structurally unsafe, failing due to poor energy dissipation, high seepage, and lack of stability against external forces.

4.5 Farmers' Irrigation Scheduling, Water Management and Institutional Performance

The findings defined in this section derive from data collected through, observation, household questionnaires, key informant interviews, and group discussions with the Karfe kebele administrative leaders and Bishoftu Oromia agriculture and land administrative office (irrigation department leaders) involved in the irrigation scheme. These approaches yielded both quantitative and qualitative insights regarding irrigation scheduling practices, water management, and institutional performance.

This section examines both the observed problems and the positive practices within the study area in relation to irrigation scheduling, water management, and institutional arrangements. The analysis is based on respondents' responses (in percentages), field observations, and discussion of the findings. It highlights the key operational and management constraints affecting the system, alongside existing good practices that support irrigation performance. Finally, an overall summary is presented to integrate the main issues and positive aspects and to draw key implications for improving the irrigation scheme.

4.5.1 Socio-Economic Characteristics of Respondents

This section outlines the socio-economic profile of the respondents surveyed, encompassing essential demographic and economic factors such as age, gender, marital status, education level, occupation, and household characteristics. These variables are crucial for comprehending their background and for the interpretation of the study's findings.

Table 4.24: Socio-economic profile of irrigation users' in Karfe scheme

Variable	Category	Number	Present (%)
Sex	Male	56	90.32
	Female	6	9.68
Age (years)	18–30	5	8.06
	31–45	21	33.87
	46–60	33	53.23
	>60	3	4.84
Education level	Illiterate	41	66.13
	Primary	12	19.35
	Secondary	7	11.29
	Above secondary	2	3.23
Farming experience	<5 years	37	59.68
	5–10 years	12	19.35
	11–20 years	8	12.90
	>20 years	5	8.06
Landholding size (ha)	<0.5	5	8.06
	0.5–1.0	19	30.65
	1–2	31	50.00
	>2	7	11.29

The findings reveal that irrigation activities are predominantly carried out by male farmers (90.32%), with minimal involvement of females (9.68%). The majority of respondents are within the 46–60 years age group (53.23%), indicating that irrigation farming is largely undertaken by older individuals.

Educational attainment is generally low, as 66.13% of the respondents are illiterate, which may hinder the adoption of improved irrigation technologies and practices. Additionally, most farmers (59.68%) have less than five years of farming experience, suggesting limited exposure to irrigation management.

Regarding landholding, the majority of farmers are smallholders, with 50% owning between 1–2 hectares. Overall, these socio-economic conditions may influence water management efficiency and the adoption of modern irrigation practices within the scheme.

4.5.2 Irrigation Scheduling

4.5.2.1 Decision-Making in Irrigation Scheduling

Decision-making in irrigation scheduling pertains to the process of identifying who is accountable for determining the timing and method of irrigation water application within the study area. It shows the degree of control and involvement of farmers, (WUA), and local administration in the management of irrigation water. This result is shown below table based on questioner with its respondents of 162 percentages in table 4.15

Table4.25 the irrigation scheduling practise in the scheme

Who decides irrigation scheduling?	Number of Response	Present (%)
Farmers/households	19	30.65
Fixed rotational system	41	66.13
Water user Association(WUA)	2	3.23
Kebele administration	0	0.00
Total	62	100.00

The findings show that irrigation scheduling is predominantly controlled by a fixed rotational system, representing 66.13% of the responses. This indicates that water distribution mainly follows a predefined schedule rather than being based on actual crop water needs.Around 30.65% of respondents stated that scheduling decisions are made at the household level, showing some degree of farmer participation.

However, the involvement of the Water Users Association (WUA) is minimal (3.23%), and there is no contribution from the kebele administration.

In general, the reliance on fixed rotation with limited institutional participation may reduce the flexibility and efficiency of water management within the scheme.

4.5.2.2 Irrigation Scheduling Practices

This refers to the main factor farmers use to decide when and how much to irrigate their fields, such as water availability, fixed rotation, soil moisture, or crop condition. According to this choice farmers of the scheme give the following information in table 4.17 below.

Table 4.26: irrigation timing Scheduling method

What criteria do you use to schedule irrigation?	Number of Response	Present (%)
Based on water availability	21	33.87
Observation of crop leafs & soil moisture	39	62.90
Fixed rotation	2	3.23
Total	62	100

The results indicate that the majority of farmers (62.90%) schedule irrigation based on observation of crop leaves and soil moisture conditions. This suggests that farmers mainly rely on traditional and experience-based methods to determine irrigation timing. About 33.87% of respondents depend on water availability, indicating that access to water also plays a significant role in scheduling decisions. Only a small proportion (3.23%) follows a fixed rotational system.Overall, the dominance of visual observation and water availability implies limited use of scientific or modern irrigation scheduling techniques, which may affect water use efficiency and optimal crop production.

4.5.2.3 Awareness

Awareness refers to farmers' knowledge of proper irrigation scheduling and efficient water management practices. Based on the observation and respondents result in Karfe scheme, awareness is generally low, so most farmers depend on traditional experience rather than scientific methods, which reduce irrigation efficiency.

Table 4.27: Awareness about the irrigation scheduling of farmers

Are you aware of scheduling?	Number of Response	Present (%)
Yes	13	20.97
No	49	79.03
Total	62	100

The findings reveal that a significant majority of respondents (79.03%) lack awareness of irrigation scheduling, while only 20.97% have some level of understanding. This indicates a generally low level of knowledge regarding proper irrigation scheduling practices among farmers.

Such limited awareness can lead to inefficient water use and suboptimal irrigation management. Therefore, there is a clear need for training and awareness programs to enhance farmers' understanding and improve the effective use of irrigation water.

4.5.3 Water management Practices

4.5.3.1 Basis of Irrigation Timing Decision

This section shows the different factors farmers use to determine when to irrigate, including water availability, soil moisture condition, crop requirements, and fixed schedules, results indicated in the table 4.16 below.

Table 4.28: Irrigation Water Use Practices in the scheme

How do you decide when to irrigate?	Number of Response	Present (%)
Based on water availability	33	53.23
By looking at soil dryness	17	27.42
Based on crop needs	5	8.06
Fixed schedule	7	11.29
Total	62	100

The findings reveal that irrigation timing is predominantly determined by water availability (53.23%), followed by soil dryness observation (27.42%). A smaller proportion relies on fixed scheduling (11.29%), while only 8.06% irrigate based on crop water requirements, indicating limited use of scientific scheduling.

4.5.3.2 Irrigation Duration

This section presents the duration of irrigation practiced by farmers, indicating how long water is applied to fields during each irrigation event. Based on this the respondents percentage result is shown in the following table 4.17.

4.29: Irrigation duration in the scheme farmers practical

How long do you irrigate?	Number of Response	Percent (%)
<2 hours	6	9.68
2–4 hours	13	20.97
>4 hours	43	69.35
Total	62	100

The results indicate that most farmers (69.35%) irrigate for more than 4 hours, while 20.97% apply water for 2–4 hours. Only a small proportion (9.68%) irrigate for less than 2 hours, showing a tendency toward prolonged irrigation durations.

4.5.3.3 Irrigation Methods Used

This section outlines the irrigation techniques employed by farmers in the study region, illustrating the percentage of respondents utilizing various application methods as summarized in the table 4.19 below.

Table4.30: Irrigation method

Which method do you use?	Number of Response	Present (%)
Flood	16	25.81
Furrow	41	66.13
Border	5	8.06
Total	62	100

The findings show that furrow irrigation is the dominant method used by most farmers (66.13%), followed by flood irrigation (25.81%), while only a small proportion (8.06%) use border methods, indicating a strong preference for furrow-based application systems.

4.5.3.4 Irrigation Technology Used

This section details the irrigation tools and systems utilized by farmers in the study area, highlighting the various equipment and methods employed for the application and management of water, as illustrated in the table.

Table 4.31: Types of Irrigation Technology Used by Farmer

What type of irrigation technology do you use in your farm?	Number of Response	Present (%)
Traditional irrigation system	50	80.65
Diesel Water pumps	12	19.35
solar pumps	0	0.00
Total	62	100

The data show that the majority of farmers (80.65%) rely on traditional irrigation systems, while 19.35% use diesel water pumps. No respondents reported using solar-powered pumps, indicating very limited adoption of modern irrigation technologies in the study area.

4.5.3.5 Water Control and Infrastructure Use

This section outlines the methods employed by farmers to manage and regulate irrigation water, which encompasses the utilization of control structures and on-farm infrastructure, as illustrated in the table.

Table 4.32: Use of water control structures

Do you use control structures?	Number of Response	Percent (%)
Yes	23	37
No	39	63
Total	62	100

Most farmers (63%) do not utilize control structures, whereas only 37% have adopted them, indicating a low level of infrastructure use for regulating irrigation water. This limited adoption reflects weak water management practices and may lead to inefficient and uneven water distribution within the scheme.

4.5.4 Institutional Performance

4.5.4.1 Institutional Support and Capacity Building

This section outlines the current state of irrigation training and institutional assistance provided to farmers in the study area, highlighting whether the respondents have undergone training and received external support for irrigation management, as summarized in the table 4.19.

Table 4.33: Training and Institutional Support of the irrigation scheme

Have you been trained in irrigation?	Number of Response	Present (%)
Yes	10	16.13
No	52	83.87
Do you receive institutional support for irrigation?		
Yes	5	8.06
No	57	91.94

The results indicate that only 10.49% of farmers have received irrigation training, while 89.51% have not, showing a clear lack of capacity-building. Likewise, just 6.17% reported receiving institutional support, compared to 93.83% without support, reflecting weak extension and institutional involvement. Overall, limited training and support hinder the adoption of improved irrigation practices. Strengthening capacity-building and institutional services is therefore essential to improve irrigation efficiency and sustainability. Engagement is therefore essential to improve irrigation performance and sustainability.

4.5.4.2 Conflict Occurrence and Management

This section outlines the instances of conflicts arising within the irrigation scheme and the approaches employed to address and resolve these issues, as summarized in the table.

Table 4.34: Conflict Occurrence and Management in the Irrigation Scheme

Is there conflict?	Number of Response	Present (%)
Yes	54	87.1
No	8	12.9
The main conflict resolution method?		
Farmers/WUA	38	61.29
Kebele administration	11	17.74
Elders/committee	13	20.97

The findings indicate that a significant majority of respondents (87.10%) acknowledged the existence of conflicts within the irrigation scheme, whereas a mere 12.90% indicated the absence of such conflicts. This suggests that disputes related to water are prevalent in the region. Conflict resolution is predominantly managed by farmers and WUA at 61.29%, followed by elders and committees at 20.97%, and kebele administration at 17.74%. This illustrates that the management of conflicts is primarily dependent on local &community-based institutions.

4.5.4.3 Causes of conflict Occurrence

Table4.35: Causes of conflict in the irrigation scheme

Cause	Number of Response	Present (%)
Water shortage	27	43.55
Water theft	19	30.65
Inequity	6	9.68
Poor management	5	8.06
Irrigation schedule disputes	5	8.06
Total	62	100

The data indicate that water shortage is the leading cause of conflict (43.55%), followed by water theft (30.65%). Other contributing factors include inequitable distribution (9.68%), poor management (8.06%), and disputes over irrigation scheduling (8.06%).

These findings suggest that irrigation conflicts are mainly driven by scarcity and water theft practices. Secondary issues such as mismanagement and scheduling disagreements further exacerbate tensions among users. Overall, the results highlight the need for improved water allocation, stronger governance, and effective regulation of irrigation practices.

4.5.4.4 Maintenance Practices

This section presents the main causes of conflict occurrence in the irrigation scheme, including factors related to water distribution, management practices, and infrastructure limitations as summarized in the table.

Table 4.36: Maintenance Responsibility in the scheme

How maintenance is carried out?	Number of Response	Present (%)
Regular routine maintenance	0	0.00
Occasional/irregular	9	14.52
done by Individual farmers	42	67.74
only during emergencies	11	17.74
Total	62	100

The results indicate that irrigation scheme maintenance is predominantly carried out by individual farmers (67.74%), while 17.74% reported that maintenance is performed only during emergencies. About 14.52% indicated occasional or irregular maintenance, and none of the respondents reported the existence of regular routine maintenance. This demonstrates the absence of a structured maintenance system, which may undermine the sustainability and efficiency of the irrigation scheme.

4.5.4.6 Challenges in Irrigation Practices

This section outlines the primary challenges encountered in irrigation practices, which encompass water availability, management limitations, infrastructure difficulties, and institutional concerns, as summarized in the table 4.22.

Table 4.37: Challenges affecting the irrigation scheme

Challenge	Number of Response	Present (%)
Over-irrigation	31	50.00
Low knowledge	6	9.68
Poor infrastructure	9	14.52
water scarcity	16	25.81
Total	62	100

The findings indicate that over-irrigation is the most significant challenge (50.00%), followed by water scarcity (25.81%). Poor infrastructure accounts for 14.52%, while low knowledge represents 9.68% of the responses. These results suggest that both water management inefficiencies and resource limitations are key constraints affecting irrigation performance in the study area.

4.5.5 The Irrigation Water Users Association (IWUA)

The IWUA was established in 2013 to manage water distribution, maintenance, and scheme operations. Although it operates under a community bylaw with growing membership, its performance is limited by inadequate capacity and resource constraints.

Table 4.138: IWUA Committee Members with Responsibilities in the scheme

No	Name of members	Sex	Responsibility	Irrigated land (ha)
1	Taso Leta	M	Chairman	1
2	Alemayehu Tadesse	M	Vice Chairman	0.5
3	Birhanu Talila	M	Secretary	0.5
4	Alamishet Getu	M	Cashier	0.75
5	Asnaku Taye	F	Member	0.5

Source: from meeting date 16/02/2026

The IWUA committee consists of five members (4 males and 1 female), indicating low female participation. The committee manages water distribution, conflict resolution, and maintenance, with all members being smallholder farmers (0.5–1.0 ha), reflecting limited inclusiveness and institutional capacity.

4.5.6 Major Observed results

The irrigation scheme is affected by major technical, operational, and institutional challenges, including inadequate farm inputs, limited canal coverage, declining soil fertility, illegal water use, non-functional hydraulic structures, poor maintenance, sedimentation, weed infestation, and weak water management practices. These problems reduce water conveyance efficiency, distribution equity, and overall system performance. Although positive practices such as intercropping, livestock integration, and IWUA participation exist, the scheme's performance remains low due to deteriorated infrastructure, weak institutional support, and inadequate maintenance.

4.5.7 Farmer Management Index (FMI) Evaluation

The Farmer Management Index (FMI) was used to assess farmers' irrigation management practices, including irrigation scheduling, timing, duration, irrigation methods, use of control structures, awareness of scheduling, and participation in maintenance activities.

Based on FAO(1989),FAO (2007) and IWMI (2007), irrigation Practices were categorized as good (1.00) moderate (0.50), poor (0.25) and very poor (0.10). Similarly, Farmer Management Index (FMI) value greater than 80% indicate as very good performance, values from 60–80% indicate as good performance, values from 40–60% indicate as moderate performance, and less than 40% indicate poor performance.

Table 4.39: Assessment of the Farmer Management Index (FMI) in the scheme

No	Indicator	Observed results	P. Level	Score%
1	Irrigation scheduling	30.65% farmer-based	poor	0.25
2	Irrigation timing criteria	62.90% traditional	Moderate	0.5
3	Irrigation duration	69.35% >4 hours (over-irrigation)	Poor	0.25
4	Irrigation method used	66.13% furrow; 25.81% flood	Moderate	0.5
5	Use of control structures	63% do not use; 37% use	Poor	0.25
6	Awareness of irrigation scheduling	79.03% not aware; 20.97% aware	Very Poor	0.1
7	Maintenance participation	No regular system; mostly individual (67.74%)	Poor	0.25
8	Total Score	-		2.1
9	Number of Indicators	-		7
10	Farmer Management Index (FMI)	$\frac{\text{Total Score}}{\text{Number of Indicators}}$*100 = 2.1/7*100		**30%**

The computed FMI value of 30% indicates a poor level of farmer irrigation management performance, reflecting low adoption of improved irrigation practices, over-irrigation, and limited awareness of scientific water management.

4.6. Overall scheme performance

The overall performance index(OPI) of the Karfe SSI was computed to evaluate the whole functionality and efficiency of the system by integrating individual evaluation indicators from each specific objectives(1-4) to compare with standards, to categorized, to expires in single qualitatively value and to know focused or priority area to the improvement. To evaluated each in giving score the ratio of actual to standard value. The Allen et al.(1998) and Bos et al.(2005) overall performance classification standard was used to 'classified the scheme as OPI greater than 85% "excellent",70-85% indicates "good" 50-70% indicates "moderate" and less than 50% indicates" poor" performance. Based on this evaluated result is shorn in table below.

Table 4.40: Integrated evaluated indicators to compute overall scheme performance

No	S. objective	Indicator	Actual Value	Standards	Score	Performance
1	Water Supply Adequacy	SAR (Spatial Mean)	1.08	1	0.75	Moderate
		RSR (Mean)	1.83	≥1.0	0.75	Moderate
		Reliability Index (RI)	83%	≥90%	0.5	Poor
		Dependability Ratio (DR)	0.71	≥1.0	0.5	Poor
		Deficit Ratio (Dr)	13%	≤10%	0.5	Poor
		Average Score	—	—	0.6	Moderate–Poor
2	Delivery Performance	Conveyance Efficiency (Ec)	76.09%	≥85%	0.65	Moderate
		Conveyance Loss (CL)	23.91%	≤20%	0.6	Moderate
		Distribution	75%	70–85%	0.75	Good
		Coefficient of Variation (CV)	0.05	≤0.10	0.8	Good
		Coefficient of Uniformity (CU)	86.50%	≥85%	0.85	Good
		Delivery Performance Ratio (DPR)	0.58	≥0.75	0.55	Moderate
		Average Score	—	—	0.7	Moderate
3	Irrigation Structures Performance	Structural Condition Index (SCI)	2.48	≥3.0	0.4	Poor
		Infrastructure Effectiveness (EI)	33.93%	≥70%	0.35	Poor
		Sedimentation Severity Index (SSI)	20.9	Low severity	0.55	Moderate
		Exit Gradient (GE)	0.2	≤0.20	0.7	Borderline
		Froude Number	3.93	4.5–9	0.4	Poor
		FS Sliding	1.45	≥1.5	0.35	Fail
		FS Overturning	1.88	≥2.0	0.4	Fail
		Average Score	—	—	0.41	Poor
4	4.1.irrigation scheduling	Scientific Scheduling	20.97%	≥80%	0.25	Very Poor
		Water Availability Method	53.23%	≤20%	0.5	Poor
		Over-Irrigation (>4 hr)	69.35%	≤30%	0.5	Poor
		Irrigation Duration	>4 hr	1.5–3 hr	0.5	Poor
		Irrigation Frequency Control	Low	High	0.25	Very Poor
		Irrigation Calendar	Absent	Required	0.25	Very Poor
		Field Water Management	Poor	Good	0.5	Poor
		Average Score	—	—	0.39	Poor
	4.2Institutional practise	Farmers Satisfaction	<40%	≥75%	0.5	Poor
		Farmers Dissatisfaction	>60%	≤25%	0.5	Poor
		Training Access	<30%	≥70%	0.25	Very Poor
		Awareness Level	~21%	≥80%	0.25	Very Poor

		Institutional Support	Low	High	0.5	Poor
		WUA Participation	~50%	≥80%	0.75	Moderate
		Maintenance System	Weak	Strong	0.5	Poor
		Conflict Level	Moderate	Low	0.5	Problematic
		Average Score	—	—	0.47	
5	Ea & Es	(Ea)	54.82%	≥60%	0.6	Moderate
		(Es)	89.10%	≥90%	0.8	Good
		Average Score	—	—	0.61	Moderate

Therefore, the Overall Performance index (OPI) of the scheme is computed by taking the average performance values from each specific Objective and from application and storage efficiency of the field evaluated indicator that was obtained from scored values give based on comparing actual to the standard give from 100% to 25% accordingly. OPI computed as the sum of all sections (Si) scored values divided by the number of sections (n).

$OPI = \frac{\sum Si}{n} = \frac{(0.6+0.7+0.41+0.47+0.61)}{5} = 0.558 =$ **56%.** This value is in the range of 50-70% indicates moderate based on the standard.

Overall, the system performs moderately in conveyance, but weak institutional management, poor farmer practices, and significant structural problems dominate its performance, making the system unsustainable mainly due to institutional and infrastructure limitations.

4.7 Mitigation Strategies for Improving Irrigation System Performance

This section shows comprehensive mitigation strategies derived from the evaluation of the Karfe irrigation scheme. The assessment identified considerable inefficiencies in critical aspects of the system, such as the adequacy of water supply, the effectiveness of conveyance and distribution, the state of irrigation infrastructure, farmers' water management practices, and institutional frameworks. These shortcomings are evident in subpar performance metrics, including inconsistent water distribution (SAR imbalance), low reliability and dependability (RI and DR), high conveyance and application losses, and inadequate structural condition (SCI).

In response, a thorough array of technical, agronomic, institutional, and managerial measures is suggested. These strategies are organized in alignment with the specific objectives of the study and adhere to globally recognized standards like FAO and IWMI. The goal is to enhance hydraulic efficiency, guarantee fair and dependable water distribution, restore malfunctioning structures, improve irrigation scheduling based on crop water needs, and strengthen institutional performance to ensure the long-term sustainability of the scheme.

4.7.1 Water Supply Adequacy of the Irrigation Scheme

4.7.2.1 Observed Results and Problems

Water distribution shows clear spatial and seasonal inequity. SAR values indicate over-supply upstream (1.21 head, 1.09 middle) and shortage downstream (0.93 tail). Reliability at the tail is only 50%, and DR (0.71) shows inconsistent delivery. RSR also drops below 0.8 in February–March, indicating severe dry-season stress. Overall, there is a strong head–tail imbalance, with excess water upstream and persistent deficits downstream, especially during dry periods.

4.7.1.1 Identified problems

- ✓ Disproportionate water distribution along the canal system
- ✓ Surplus irrigation supply at the head reach and a deficit at the tail reach
- ✓ Seasonal water scarcity during February to March at the tail end
- ✓ Low reliability of water delivery at the tail Inadequate dependability of the supply system)
- ✓ Absence of coordinated irrigation scheduling among users

These issues collectively point to an ineffective and inequitable irrigation delivery system.

4.7.1.2 Mitigation Strategies

- ✓ Repair or replace head regulator gates and install simple control structures to improve water regulation and ensure equitable distribution.
- ✓ Implement and enforce a rotational irrigation schedule through the WUA for fair water allocation among head, middle, and tail users.
- ✓ Control illegal water abstraction through strengthened by law enforcement, routine canal inspections, and simple flow monitoring.
- ✓ Provide farmer training on efficient irrigation practices and apply adaptive water management during water-scarce periods.

4.7.2 Performance of Canal Water Delivery system

The efficiency of conveyance was suboptimal at 76.09%, resulting in losses approximating 23.91%. This inefficiency can be attributed primarily to seepage from unlined canals, sediment accumulation, weed proliferation, unauthorized water extraction, insufficient maintenance, and external factors including road crossings and mining operations this cause reduced downstream discharge availability

4.7.2.2Mitigation Strategies

- ✓ Repair canal lining and masonry structures to reduce seepage and damage.
- ✓ Improve sediment and weed control through settling basins and regular cleaning.
- ✓ Apply demand-based scheduling and control illegal water use via WUA.
- ✓ Protect canals from livestock, dumping, and erosion.
- ✓ Use rotational irrigation to ensure fair distribution, prioritizing tail-end users during shortages.

4.7.3 Performance of the scheme Irrigation Structures

4.7.3.1Observed Results and Problems

The assessment shows poor performance of irrigation structures, with a Structural Condition Index (SCI) of 2.48 indicating a degraded system. Key hydraulic structures, including flow regulators and the left retaining wall, are either non-functional or failed, while some were never constructed. These issues have caused uncontrolled flow, reduced efficiency, and unreliable water distribution. The situation is worsened by the absence of routine operation and maintenance, leading to further deterioration, erosion, and reduced system reliability. Overall, structural failures and weak maintenance have significantly compromised the scheme's performance and sustainability.

4.7.3.2 Mitigation Strategies

Irrigation structures should be rehabilitated and redesigned, with damaged regulators repaired and a seasonal preventive maintenance system under IWUA. The failed retaining wall should be rebuilt as a reinforced concrete gravity wall (FOS $\geq$ 1.5) with foundation below scour depth and guide bunds for flood protection. Drainage should be improved using weep holes, filters, and riprap, supported by energy dissipation measures and a dedicated IWUA maintenance fund for sustainability.

4.7.3.3 Retaining wall redesign

This section presents the redesign of the failed Karfe retaining wall, identified for urgent rehabilitation to prevent further deterioration and system failure. Based on hydraulic performance, weir axis alignment, and structural stability analysis, evaluated using six indicators; the structure is found to be hydraulically inefficient and structurally unsafe. The main causes of failure are poor energy dissipation, excessive seepage, inadequate drainage, and weak resistance to lateral and hydraulic forces. Accordingly, two alternative retaining wall systems were proposed and assessed based on their advantages and limitations.

Option 1: Stone masonry retaining wall

Option 2: Reinforced concrete cantilever retaining wall

Both options were developed to allow selection by the implementing authority during rehabilitation.

Selection of Wall Type: Based on design standards and site conditions, including: Wall height = 4.0 m, Saturated backfill condition, Seismic loading (αh = 0.10g) and Hydraulic disturbance due to weir misalignment causing local scour and uneven flow.

The reinforced concrete cantilever retaining wall is technically more suitable.

Its main advantage is that it resists lateral earth pressure through flexural action of the stem and base slab, unlike masonry gravity walls which depend primarily on self-weight.

According to Das,B.M. (2002),principles of foundation engineering and Bowless,J.E.(1996), foundation analysis and design masonry walls are more prone to sliding and overturning under saturated conditions due to reduced effective friction and increased hydraulic pressure, failures when water pressure is involved, whereas reinforced concrete cantilever walls offer improved stability due to their monolithic structure and greater flexural strength. Furthermore, the wall facilitates the integration of drainage and scour protection systems, which is crucial given the increased hydraulic concentration and erosion risk from weir misalignment. Furthermore, design guidelines from Federal Highway Administration (FHWA) (Berg et al., 2009) and (BS 8002,1994), recommended reinforced concrete cantilever retaining walls for medium-height structures in seismic, and water-affected settings due to their superior stability, durability, and long-term stability, compared to masonry options but both are designed for alternative as option 1 and option2.

Step1: problem statement and design objectives Explanation

The site is influenced by water-saturated soil, seismic loading, and misaligned flow, which generate significant lateral pressure and lead to risks of scour, sliding, and overturning. Without a proper design, the structure may become unstable and fail at the foundation.

Objective: To develop a stable, safe, and cost-effective retaining wall capable of withstanding earth pressures water pressure, preventing overturning, sliding, and bearing failure, while ensuring adequate drainage and protection against scour.

Opetion-1 Stone Masonry retaining wall design

Step 2: Design Data collection

Table 4.41: Summary of Design Input Data and Assumptions

Parameter	Value	Source
Wall height (H)	4.0 m	From original design
Masonry unit	Stone masonry with cement mortar 1:4	IS 1905:1987
Grouted vertical reinforcement	Φ12 @ 1.0 m c/c	BS 5628:2005
Backfill	Saturated & earthquake (critical case)	IS 1905:1987
Unit weight of masonry (γm)	22 kN/m³	IS 875 (Part 1):1987
Unit weight of saturated backfill (γsat)	20 kN/m³	Bowles (1996)
Angle of repose (φ)	30°	Assumed
Coefficient of friction (μ)	0.55	IS 1905:1987,Das (2011)
Earthquake coefficient (αh)	0.10 g	IS 1893 (Part 1):2016
Allowable bearing pressure (qa)	150 kPa	Terzaghi (1943)
Foundation depth (Df)	1.2 m below finished grade	BS 6031:2009
Scour depth allowance	0.4 m	Maynord (1995)
Lean concrete layer	0.10 m thick	Under entire base
Concrete cover (bottom/back)	50 mm	ACI 318-14
Concrete cover (others)	40 mm	EN 1992-1-1
Backfill compaction	95% MDD	BS 6031:2009
base width (b)	2.5 m	Starting assumption
Toe length (initial)	0.6 m	Front of wall
Heel length (initial)	1.3 m	(2.5 - 0.6 - 0.6)
Base slab thickness	0.5 m	Uniform
Stem height	4.0 m	Above base
Stem thickness at base	0.60 m	Starting assumption
Stem thickness at top	0.40 m	Starting assumption
Shear key depth (initial)	0.5 m	Below base
Shear key width	0.4 m	Starting assumption
Drainage	Weep holes @ 1.5 m c/c	CIRIA C516 (2000

Step 3: Initial dimensions

Using design guide lines empirical of J.E, Bowless (1996) and Terzaghi (1996)

1. Base width: =0.8H=0.8*4m =3.2m ≈ 3.5m to balance the moment, reduce toe pressure and improve stability
2. Toe Length (1.0 m):Toe is generally taken as 25%–35% of base width Toe = 0.3B = 0.3×3.5 = 1.05m
3. Heel Length :Heel=B−Toe−Stem thickness ,Heel length (m) = 3.5−1.0−0.5 = 2.0 m, it must be larger to carry backfill weight (main stabilizing force)
4. Base Thickness (m): = 0.1H to 0.15H ,0.1×4 = 0.4 m to 0.15×4 = 0.6 m, from this 0.45m is selected in order to safe for bending and shear and it's economical.
5. Stem Thickness (m): Based on standard proportions: base thickness = 0.1H = 0.1*0.4=0.5 m and top thickness: = 0.2 to 0.3 m =0.25m.
6. Shear Key Depth (m): Initially assumed smaller (0.5–0.6 m), but Sliding check failed → increased depth.so take as 0.75m.Final value obtained from Passive resistance equation: Pp = $\frac{1}{2}$Kpγd^{2}P.Where: Pp is Passive earth pressure force (kN/m), Kp is Coefficient of passive earth pressure, Γ is Unit weight of soil (kN/m³),d is Depth of embedment (m) and ½ is Pressure distribution factor.Depth increased until: FSsliding ≥1.5 .

Step 4: Active Earth Pressure (Saturated Backfill + Earthquake).

Based on Khan et al.(2024), Monotone -Okabe methods were used for seismic active earth pressure. This method is widely used in geotechnical earthquake engineering to estimate the additional lateral earth pressure induced by seismic inertia forces acting on the backfill soil.

The seismic earth pressure coefficient (Kae) is given by the Mononobe–Okabe formulation:

$$Kae = \frac{\cos^2(\varphi - \theta - \beta)}{[\cos\theta \cos^2\beta \cos(\delta + \beta + \theta) \times (1 + \sqrt{(\sin(\varphi+\delta)\sin(\varphi-\theta-\beta)/\cos(\delta+\beta+\theta)\cos(\beta-\theta))^2}]}$$

For vertical wall parameters simplified as: Wall inclination: β=0 and Wall friction: δ=0 (masonry backfill condition). Seismic angle: $\theta=\tan^{-1}(\alpha h)=\tan^{-1}(0.10) = 5.71^\circ$ For practical design purposes, the seismic coefficient is commonly simplified. Static active earth pressure coefficient: Ka ≈ 0.33 and Seismic active earth pressure coefficient: Kae≈0.45.The Horizontal seismic earth pressure (saturated backfill) acting on the retaining wall is then calculated as:Ph = ½ × Kae × γ_{sat} × H².Then, substitute the values: Ph = ½ × 0.45 × 20 × 4.0² =72kN/m.

The resultant seismic active earth pressure acts at a height of: The resultant of triangular earth pressure distribution acts at H/3 above the base, while uniformly distributed surcharge loads act at H/2.Based on this way, seismic active earth pressure acts at H/3: H/3 = 1.33 m above base.

Step 4: Computation of Total Lateral Earth Pressures (Soil, Water, and Surcharge Effects)

(a) Seismic active earth pressure (from previous step): The seismic active earth pressure has been computed as: Ph = 72KN/m, acted at H/3 =4/3 = 1.33m above base.

(b) Water pressure (Pw): is assumed for additional pressure (saturated backfill, no drainage assumed for worst case), based on Das et al.(2011), and explained as hydrostatic pressure on retaining walls computed as: $Pw = ½ \times γw \times H^2$,$Pw = ½ \times 10 \times 4.0^2$,Pw = 80 kN/m.This pressure acts at H/3 = 1.33 m above the base section of the wall.

(c) Surcharge pressure (Ps): A uniformly distributed surcharge load of 10kN/m² was adopted for access and maintenance purposes in accordance with (BS, 1994), which recommends considering nominal surcharge loads on retaining walls to account for construction traffic and operational maintenance activities.Ps = Ka×q×H=0.45×10×4.0=18 kN/m,Acts at H/2= 2.0 m above base.

(d) Total horizontal force (ΣH):Based on Berg et al.(2009), at Drainage reduces hydrostatic pressure.

Case 1: Without drainage (worst case):ΣH = Ph + Pw+Ps = 72 + 80+18 = 170kN/m

Momentum about the base: ΣMot = (72×1.33) + (801.33) + (18×2.0)=238.2 kN·m/m

Cause2: With drainage (weep holes plus granular backfill): Drainage removes hydrostatic water pressure, therefore:ΣH=Ph+Ps = 72+18 = 90 kN/m.Moments of overturning: ΣMot = (72×1.33) + (18×2) and ΣMot overturning = 95.8+36.0=131.8 kNm/m

Step 5: Vertical Load Analysis and Stabilizing Forces Evaluation

Assumptions: Base friction angle: $δ=0^0$ (masonry–soil interface) and Vertical are evaluated based on self-weight of the wall components and back fill. Pv = Ph × tan (δ) = 72kn/m*tan (0) = 0, (δ = 0 for masonry).

Geometry: Base width b=2.5 m Toe = 0.6 m ,Stem base thickness = 0.6 m ,Heel = 1.3 m

Table 4.42: summarized Vertical Forces and Moments

Component	Formula	Calculation	Force (kN/m)	from toe (m)	Moment (kN·m/m)
Wall stem	Astem*γc	0.5 × 4.0 × 22	44	0.9	39.6
Wall base	b*t*γc	2.5 × 0.5 × 22	27.5	1.25	34.4
Backfill on heel	Lheel*H*γsat	1.3 × 4.0 × 20	104	1.85	192.4
Surcharge on heel	Q*Lheel	1.3 × 10	13	1.85	24.1
Shear key	Bk*dk*γc	0.5 × 0.4 × 22	4.4	0.8	3.5
ΣV			192.9 kN/m		ΣMstab = 294.0

Total vertical loads (ΣV) are 192.9kN/m and Total Stabilizing Moment (ΣMsta) is 294kNm/m.

Step 6: Stability analysis of the trial Section

According to the Das et al.(2011), principle the masonry retaining wall stability was evaluated against overturning and sliding failure modes under both drained and un-drained conditions.a,Overturning checking using (b=2.5m, d=0.5m):The factor of safety against overturning is given by: $FSot=\frac{\Sigma Mstab}{\Sigma Mot}$.

Cause 1: With Drainages: $FSot=\frac{\Sigma Mstab}{\Sigma Motoverturning} = \frac{294}{131.8} = 2.23 \geq 2.0$ ----------------- OK (Close to standard)

Cause 2: Without Drainage: $FSot = \frac{\Sigma Mstab}{\Sigma Mot} = \frac{294}{238.2} = 1.23 < 2.0$ ------------------- Not Ok

(b) Sliding check (b=2.5m, d=0.5m):The factor of safety against sliding is:Passive resistance from shear key 0.5 m deep: $Pp = \frac{1}{2} \times Kp \times \gamma sat \times d^2$, $Kp =\frac{(1+\sin\varphi)}{(1-\sin\varphi)} = \frac{(1+0.5)}{(1-0.5)} = 3.0$, $Pp = \frac{1}{2}\times 3.0 \times 20 \times 0.5^2 = 7.5$ kN/m

Cause 1: With drainage: $FSsliding = \frac{(\mu \times \Sigma V + P_p)}{(\Sigma H)} = \frac{(0.55\times 192.9+7.5)}{90} = 1.26 < 1.5$--------- not ok.

Cause 2: Without drainage: $FSsliding = \frac{(\mu \times \Sigma V + P_p)}{(\Sigma H)} = \frac{(0.55\times 192.9+7.5)}{170} = 0.67 < 1.5$------------not ok.

Table 4.42: Summary of Stability analysis

Check	With Drainage	Without Drainage	Requirement	Status
FSoverturning	2.23	1.23	≥ 2.0	Not Ok! without drainage
FS sliding	1.26	0.67	≥ 1.5	Not Ok! both cases

The trial section with base width (b = 2.5 m) and shear key depth (d = 0.5 m) is unstable against sliding in both drained and un-drained conditions, and also fails overturning under un-drained conditions.

Therefore, the design is unsafe and not acceptable, and improvement is required by: Increasing base width, Increasing shear key depth and improving drainage system to reduce hydrostatic pressure

Step 7 : Design Optimization through Iterative Base Width (b = 3m, d = 0.6m)

Table 4.43: Revised dimension values

Parameter	Value	Calculation
Base width (b)	3.0 m	Increased from 2.5m to 3m
Toe	0.6 m	Unchanged
Stem base	0.6 m	Unchanged
Heel	1.8 m	3.0 - 0.6 - 0.6 = 1.8 m
Shear key depth	0.6 m	Increased from 0.5 m to 0.6

i) Vertical Forces (ΣV) for b=3.0m ,Toe= 0.6m,Stem base thickness= 0.6m and Heel= 3.0-0.6-0.6= 1.8m

Table 4.44: Vertical Forces and Moments using revised values

Component	Formula	Calculation	Force (kN/m)	Lever arm from toe (m)	Mo'nt (kN·m/m)
Wall stem	Astem*γc	0.5 × 4.0 × 22	44	0.9	39.6
Wall base	b*t*γc	3.0 × 0.5 × 22	33	1.5	49.5
Backfill on heel	Lheel*H*γsat	1.8 × 4.0 × 20	144	2.1	302.4
Surcharge on heel	q*Lheel	1.8 × 10	18	2.1	37.8
Shear key	Bk*dk*γc	0.6 × 0.4 × 22	5.3	0.8	4.2
ΣV			244.3		433.5

ΣV=244.3KN/m and ΣMstab = 433.5 kN·m/m

ii) Stability check, when b=3m, and d=0.6m

Table 4.45: Stability Results (Preliminary Check)

Check	With Drainage	Without Drainage	Requirement	Status
FSoverturning	3.29	1.82	≥ 2.0	Not Ok! without drainage
FS sliding	1.61	0.85	≥ 1.5	Not Ok! without drainage

iii) Passive earth resistance from (shear key) at 0.6 m deep, $P_p = \frac{1}{2} \times 3.0 \times 20 \times 0.6^2 = 10.8$ kN/m

iv)Final Stability Results

Table 4.46: Final Stability Summary

Check	Formula	Value	Requirement	Status
FS overturning (drained)	$\frac{433.5}{131.8}$	3.29	≥ 2.0	Ok!
FS sliding (drained)	$\frac{(0.55 \times 244.3 + 10.8)}{90}$	1.61	≥ 1.5	Ok!
FS overturning (no-drained)	$\frac{433.5}{238.2}$	1.82	≥ 2.0	Not Ok!
FS sliding (no-drained)	$\frac{145.2}{170}$	0.85	≥ 1.5	Not Ok!

Conclusion: At b = 3.0 m, the retaining wall is: Safe under drained conditions (FS overturning = 3.29, FS sliding = 1.61) and Unsafe under no-drainage conditions.

Therefore, although structural safety improves significantly, the system remains sensitive to drainage conditions. Further optimization of base width and shear key depth is required to ensure full stability under all conditions.

Step 8: Final Stability Verification for Optimized Masonry Wall (b = 3.5 m)

To enhance the overall stability of the retaining wall under both drained and critical loading conditions, the base width and shear key depth were further optimized. The modified section was subsequently evaluated through detailed stability analyses to verify its safety against overturning and sliding failures.

Table 4.26: Revised dimension values

Parameter	Value	Calculation
Base width (b)	3.5 m	Increase to 3.5m from 3m
Toe	0.6 m	Unchanged
Stem base	0.6 m	Unchanged
Heel	2.3 m	3.5 - 0.6 - 0.6 = 2.3 m
Shear key depth	0.75 m	Increased from 0.6 to 0.75m

(a)Vertical Forces analysis (ΣV):For the revised section at: Base width, b (3.5m), Toe length (0.6m),Stem base thickness(0.6m) &Heel length (2.3m).

Table 4.47: Vertical Forces and Moments using the new revised values

Component	Calculation	Force (kN/m)	Arm from toe (m)	Moment (kN·m/m)
Wall stem	0.5 × 4.0 × 22	44	0.9	39.6
Wall base	3.5 × 0.5 × 22	38.5	1.75	67.4
Backfill on heel	2.3 × 4.0 × 20	184	2.35	432.4
Surcharge on heel	2.3 × 10	23	2.35	54.1
Shear key	0.75 × 0.4 × 22	6.6	0.8	5.3
ΣV		296.1		598.8

ΣV=296.1 kN/m and ΣMstab=598.8 kNm/m

(b) Stability check, when b=3.5m and d=0.75m

Passive resistance from shear key 0.75 m deep = Pp = ½ × 3.0 × 20 × 0.75^2 = 16.9 kN/m

Table 4.48: Stability Analysis Results for with-Drained and without drained Conditions

Check	Formula	Value	Requirement	Status
FS overturning (drained)	$\frac{598.8}{131.8}$	4.54	≥ 2.0	Ok!
FS sliding (drained)	$\frac{(0.55\times296.1 + 16.9)}{90}$	2	≥ 1.5	Ok!
FS overturning (no-drained)	$\frac{598.8}{238.2}$	2.51	≥ 2.0	Ok!
FS sliding (no-drained)	$\frac{179.8}{170}$	1.06	≥ 1.5	Not Ok!

Remarks: The revised wall section is safe against overturning under both drained and un-drained.

Sliding stability under drained conditions is satisfactory, with FS = 2.00 > 1.5. Under un-drained conditions, sliding stability is inadequate, with FS = 1.06 < 1.5.

Proper drainage systems are necessary to reduce hydrostatic pressure and improve wall stability. Therefore, the optimized section (b=3.5 m, d=0.75 m) is acceptable only when effective drainage is provided.

Step 9.Base Pressure Analysis when (b = 3.5 m, Drained)

According to the bearing capacity and eccentricity concepts developed by (Terzaghi,1943), the base pressure beneath the retaining wall was analysed to assess the safety of the foundation against excessive bearing pressure and the occurrence of tensile stresses.

i)Net Stabilizing Moment:ΣMnet = ΣMstab− ΣV = 598.8−131.8 = 467.0 kN·m/m

ii) Location of Resultant force from toe = $\frac{\Sigma \text{Mnet}}{\Sigma \text{V}} = \frac{4697}{296.1}$ = 1.58 m

iii) Eccentricity Check (E): E= $\frac{b}{2}$ −1.58 = $\frac{3.5}{6}$ .1.583 = 1.75−1.58 = 0.17m ≤ 0.583----------------- Ok

Therefore, the resultant lies within the middle third of the base, indicating that no tensile stress develops beneath the foundation.

iv)Maximum Base Pressure:Pmax = $\frac{\Sigma V}{b} \times (1 + \frac{6e}{b}) = \frac{296.1}{3.5} \times (1 + \frac{6\times 0.17}{3.5})$ = 84.6×1.291 = 109.2kpa.

v)Minimum Base Pressure:Pmin = 84.6× (1−0.291) = 60.0 kPa -----Pmin>0, no tension occurs beneath the foundation base.

Vi) Bearing Capacity Check: Considering the foundation embedment depth Df =1.2m,qa = 150+ (20×1.2) = 174 kPa and Pmax=109.2 kPa<qa=174 kPa-------------OK

Therefore, the maximum base pressure is less than the allowable bearing capacity of the soil, indicating that the foundation is safe against bearing failure under drained conditions.

Step.10 Sliding Stability Check Considering Foundation Embedment and Passive Earth Pressure

To improve sliding resistance, the passive earth pressure developed in front of the embedded foundation was considered. The embedment depth of the foundation was taken as Df = 1.2 m. Sliding Stability Check Considering Foundation Embedment and Passive Earth Pressure

Passive Earth Pressure in Front of Foundation: With foundation depth Df = 1.2 m ,Ppassive_front = ½ × Kp × γsat × Df^2 = ½ × 3.0 × 20 × $(1.2)^2$ = 43.2 kN/m,Factor of Safety against Sliding: FSsliding = $\frac{(\mathbf{0.55 \times 296.1 + 16.9 + 43.2})}{\mathbf{90}} = \frac{\mathbf{223}}{\mathbf{90}}$ = 2.48 ≥ 1.5-----------Ok.Therefore, the retaining wall is safe against sliding after considering the contribution of passive earth resistance due to foundation embedment.

Step.11. Structural design/reinforcement

The structural design of the masonry retaining wall was carried out in accordance with the provisions of BS 56, 2010) and (IS 1905, 1987). Reinforcement was provided to ensure adequate resistance against bending, shear, and cracking under the combined effects of earth pressure, surcharge load, and seismic loading.

A.Stem-main vertical reinforcement

The maximum bending moment occurs at the base of the stem.Moment at base of stem = 131.8 kN·m/m, Stem thickness at base = 0.60 m = 600mm, Cover= 50mm (back face) and Assume Φ16 bar.

Effective depth: d= (600-50-8) =542mm

Required steel area: $As = \frac{M}{(0.87fy \times 0.9\ d)} == \frac{131.8}{(0.87 \times 415 \times 0.9 \times 542)} = \frac{131.8 \times 10\text{^}6}{(0.87 \times 415 \times 487.8)}$ = 748.35≈ 749 mm²/m

Provide ϕ16 bars at 150 mm center-to-center spacing and Number of bars per meter: $= \frac{1000}{150} = 6.67$

Then steel area per meter:AS = 6.67× $(\pi \times \ \frac{16^2}{4})$ = 6.67*201mm^2 = 1340.67 ≈ 1341 mm^2/m

Provide Φ16 @ 150 mm c/c (As = 1341 mm²/m) grouted in masonry cavities.

B.Stem-distribution horizontal reinforcement

Gross cross-sectional area per meter width (Ag):Ag = 600 × 1000 = 600,000 mm²/m

Minimum reinforcement: As (min) = 0.0007×600000 = 420 mm²/m

Using ϕ12 bars at 250 mm spacing: $As = \frac{1000}{250} \times 113$ = 452 mm²/m

Provide: Φ12 @ 250mm c/c (As = 452mm²/m) on both faces of the wall.

C. Base Slab Toe Reinforcement:*Toe length = 0.6 m*

Max base pressure= 109.2 kpa Bending moment at toe: $Mtoe = \frac{109.2 \times (0.6)2}{2}$ =19.656 ≈ 19.7 KN.m/m

Base slab thickness =500 mm, Cover =50 mm and Assume ϕ12 bars.

Effective depth: d= $500\text{-}50\text{-}\frac{12}{2}$ = 444mm (assume Φ12 bar)

Required reinforcement: $As = \frac{M}{(0.87fy \times 0.9\,d)} = \ \frac{19.7 \times 10\text{^}6}{0.87 \times 415 \times 0.9 \times 444)}$ = 136.54≈ 137 mm²/m

Number of bars per meter: $As = \frac{1000}{300} = 3.33$

Then steel area per meter: As = 3.33× $(\pi \times \frac{12^2}{4})$ = 3.33×113.04mm^2 = 376.42 ≈ 377 mm^2/m

As = Provide Φ12 @ 300mm c/c (As = 377 mm²/m) –minimum reinforcement.

D. Base slab-Heel top reinforcement: The heel slab is subjected to backfill and surcharge loads.

Base Slab-Heel Top Reinforcement (heel width=2.3m)

Table 4.50: Calculation of Loads and Bending Moment on Heel Slab of Retaining Wall

Load	Calculation	Force (kN/m)	Arm (m)	Moment (kN·m/m)
Backfill (80 kPa)	80 × 2.3	184	1.15	211.6
Surcharge (10 kPa)	10 × 2.3	23	1.15	26.5
Total Mheel				238.1

Therefore: Mheel (238.1KN.m/m). Base slab thickness (500mm), Cover (40mm) and assume ϕ20 bars.

Effective depth: d = 500-40-$\frac{20}{2}$ =450mm

Required steel area: As = = $\frac{M}{(0.87fy \times 0.9\,d)} = \frac{M238.1 \times 10\text{^}6}{(0.87 \times 415 \times 0.9 \times 450)}$ = 1628.3≈ 1629 mm²/m

Number of bars per meter = 1000/150 = 6.67.Then steel area per meter As= 6.67× (π× 20^2/4) =

As= 6.67*314mm^2 = 2094.38≈ 2095 mm^2/m.Hence, provide: Φ20 @ 150mm c/c (As = 2095 mm²/m) as top reinforcement in the heel slab.

E. Shear Key Reinforcement, Shear key dimensions: Depth =0 75m,Depth=0.4m To improve sliding resistance and structural integrity, provide:

Provide Φ12 @ 200 mm each face (concrete key), tied with Φ8 @ 300 mm using stirrups, (Terzaghi et al., 1996), about Shear key design.

Step.12 Foundation and Construction details

Based on BS (2020) recommendation the retaining wall foundation was designed and constructed on properly prepared and stable ground to ensure adequate resistance against settlement, sliding, and scour. Weak or unsuitable foundation materials were excavated and replaced with compacted fill or lean concrete as required. Furthermore, appropriate drainage provisions, controlled backfilling, and strict construction quality measures were implemented to enhance the structural stability, durability, and long-term performance of the retaining wall.

Table.4.51: Foundation and Construction Details of Masonry Retaining Wall

Item	**Value**
Foundation depth (Df)	1.2 m below finished grade (increase to 1.5 m at scour zone)
Total excavation depth	1.7 m (1.2 m + 0.5 m base)
Lean concrete	0.10 m C10 under entire base
Base material	Reinforced concrete (not masonry)
Stem material	Stone masonry with cement mortar 1:4
Concrete cover – bottom/back	50 mm
Concrete cover – other faces	40 mm
Backfill compaction	95% MDD
Drainage	Weep holes @ 1.5 m c/c + 300 mm granular backfill
Waterproofing	Bituminous coating on back face of masonry

Step 13.Scour Protection (Due to 12.4° Weir Deviation)

Because of the hydraulic impact caused by the 12.4° deviation of the weir axis, additional scour protection measures were incorporated to minimize erosion and prevent undermining of the retaining wall foundation.

Table 4.52: Foundation Design Parameters and Construction Specifications

Measure	Specification
Riprap apron at toe	2.0 m wide × 0.6 m thick
Riprap stone size	200–400 mm
Filter layer	200 mm coarse sand + geotextile
Foundation depth in scour zone	Increase to 1.5 m at left toe
Toe wall (concrete)	0.5 m deep × 0.3 m wide to prevent under-scour

Step14 .Final design summary Summary of Masonry Retaining Wall.

Table 4.53: Summarized final design dimension values

Parameter	Final Value	Determined By
Total base width (b)	3.5m	Stability (FSsliding =2.0)
Toe length	0.6 m	Assumed
Heel length	2.3m	b - toe - stem = 3.5 - 0.6 - 0.6
Base slab thickness	0.5m	Assumed
Stem thickness at base	0.60 m	Assumed
Stem thickness at top	0.40m	Assumed
Shear key depth	0.75m	Stability iteration(Pp=16.9kN/m)
Shear key width	0.4m	Assumed
Foundation depth (Df)	1.2m (1.5m at scour zone)	Scour allowance
μ (coefficient of friction)	0.55	IS 1905:1987
K aseismic	0.45	Monotone-Okabe
Stem vertical reinforcement	Φ16@150mm c/c (back face)	Back face
Stem-horizontal reinforcement	Φ12@250 mm c/c (both faces)	Back face
Toe bottom reinforcement	Φ12@ 300mm c/c	Bottom reinforcement
Heel top reinforcement	Φ20 @150mm c/c	Top reinforcement
Shear key reinforcement	Φ12@200mmc/c+Φ8@300mm stirrups	Structural requirement

Table 4.54: Final Stability Check Results of Retaining Wall Design

Check	Formula	Value	Requirement	Status
FSoverturning	$\frac{\Sigma Mstab}{\Sigma Mot}$	4.54	≥ 2.0	Ok!
FSsliding (with key)	$\frac{(\mu\Sigma V + Pp)}{\Sigma H}$	2.00	≥ 1.5	Ok!
FSsliding (with embedment)	$\frac{(\mu\Sigma V + Pp + Pfront)}{\Sigma H}$	2.48	≥ 1.5	Ok!
Eccentricity(e),	$\frac{b}{2} - \frac{\Sigma V}{\Sigma M}$	0.17m	≤ b/6=0.583	Ok!
Maxbase pressure(Pmax)	$\frac{\Sigma V}{b}(1+\frac{6e}{b})$	109.2	≤174	Ok!

The final optimized retaining wall section satisfies the requirements for overturning stability, sliding resistance, eccentricity, and allowable bearing pressure under the considered loading conditions.

Step.15: Bill of quantity and engineering cost estimates Option-1 (Masonry wall)

Table 4.55: Detail work cost estimation of the masonry retaining wall

Item	Description	Unit	Quantity	Unit price (birr)	Total amount (birr)
1	Site clearing and removing top soil (6m width×30m length)	m^2	180.00	106.00	19,080.00
2	Excavation (3.5m width×1.7m depth) and toe trench 0.6m×0.6m×1m, heel 0.3m×1.7m×1m	m^3	204.60	998.00	204,190.80
3	0.1m thick & 3.5m width Lean Concrete C-10 under entire base and 0.6m×0.1m×1m under toe trench	m^3	12.30	12,970.00	159,531.00
4	0.5m thick Reinforced Concrete Base Slab (C-25/30)	m^3	52.50	20,393.00	1,070,632.50
5	Reinforced Concrete Shear Key (0.4m width×0.75m depth)	m^3	9.00	20,393.00	183,537.00
6	Stone Masonry Stem (1:4 mortar) wih 4m height and 0.5m avg.thickness	m^3	60.00	9,817.00	589,020.00
7	Reinforcement – Base slab bottom (Φ12 @ 300 c/c)	kg	88.78	342.00	30,363.96
8	Reinforcement – Base slab top (Φ20 @ 150 c/c)	kg	493.37	342.00	168,733.40
9	Reinforcement – Shear key (Φ12 @ 200 c/c each face + Φ8 @ 300 stirrups)	kg	259.50	342.00	88,749.00
10	Reinforcement – Stem vertical (Φ16 @ 150 c/c back face)	kg	1263.22	342.00	432,021.92
11	Reinforcement – Stem horizontal (Φ12 @ 250 c/c both faces)	kg	212.89	342.00	72,809.06
12	Backfill (saturated, 95% MDD), heel length 2.3m and height 4m	m^3	276.00	1,200.00	331,200.00
13	Granular drainage layer (500 mm thick behind stem) with around 4m	m^3	60.00	3,200.00	192,000.00
14	Weep holes (75 mm dia @ 1.5 m c/c)	No.	20.00	225.00	4,500.00
15	Waterproofing (bituminous coating on back face), 4m height	m^2	120.00	550.00	66,000.00
16	Riprap scour protection (2.0 m wide × 0.6 m thick)	m^3	36.00	3,200.00	115,200.00
17	Filter layer (200 mm coarse sand + geotextile), 2m width	m^2	60.00	455.00	27,300.00
Total amount in birr before Vat 15%					**3,754,868.64**
Vat 15%					**563,230.30**
Total amount in birr with Vat 15%					**4,318,098.94**
Contigency 10% in birr					**431,809.89**
Grand Total in birr					**4,749,908.83**

Step.16: Work schedule in 8 hour working day for Masonry Retaining wall

Table 4.56: Detailed Activities of the construction Work

Activity	Days
1. Clearing and removing	2
2. Excavation	3
3. Lean concrete	1
4. Base slab reinforcement	2
5. Base slab concrete	1.5
6. Shear key concrete	1.5
7. Stem missionary	8
8. Stem reinforcement (grouted)	3
9. Backfill and Drainage	3
10. Weep holes and waterproofing	2
11. Scour protection	2
Total in Day	29

Option 2: Reinforced Concrete Cantilever Wall

This study employs a reinforced concrete cantilever retaining wall due to its effectiveness and appropriateness for moderate to high earth pressures. The wall counteracts lateral forces through the cantilever action of its stem and base slab, leveraging both its own weight and the weight of the retained soil, rendering it more cost-effective than gravity walls. Additionally, it ensures sufficient stability against sliding, overturning, and bearing failure, while also offering good durability and ease of construction given the site conditions (BS 8110-11997, 2020; Das et al., 2011; Bowless, 1996).

Step.1 Design data collection and assumptions

Table 4.57: List of Design Input Data and Assumptions

Parameter	Value	Sources
Wall height (H)	4.0 m	From design document
Concrete grade	C25/30 (f'c = 25/30 MPa)	BS 8110-11997
Steel grade	Fe 415 (fy = 415 MPa)	IS 1786:2008
Backfill	Saturated + earthquake(critical)	Assumed
Unit weight of concrete (γc)	25 kN/m³	Standard values
Unit weight of saturated backfill (γsat)	20 kN/m³	Bowles (1996)
Angle of repose (φ)	30°	Assumed
Coefficient of friction (μ)	0.55(concrete on weathered basalt)	Das (2011)
Earthquake coefficient (αh)	0.10 g	Assumed
Allowable bearing pressure (qa)	150 kPa (weathered basalt)	Terzaghi (1943)
Foundation depth (Df)	1.2 m below finished grade	Frost protection + scour
Scour depth allowance	0.4 m	Maynord (1995)
Lean concrete layer	0.10 m thick	Under entire base
Concrete cover (bottom/back)	50 mm	ACI 318-14
Concrete cover (others)	40 mm	EN 1992-1-1
Backfill compaction	95% MDD	BS 6031:2009
Total base width (b)	3.5 m	0.875H
Toe length	1.0 m	Front of wall
Heel length	2.0 m	Under backfill (3.5-1.0- 0.5)
Base slab thickness	0.45 m	Uniform
Stem height	4.0 m	Above base
Stem thickness at base	0.50 m	Assumed
Stem thickness at top	0.25 m	Assumed
Shear key depth	0.75 m	Below base
Shear key width	0.4 m	Assumed
Drainage	Weep holes @ 1.5 m c/c	Standard drainage practice

Step 2: Load Calculations (Saturated Backfill + Earthquake)

This section assesses all lateral and vertical forces exerted on the retaining wall during the most adverse conditions, which encompass earthquakes and saturated backfill. Those are:

1. Active Earth Pressure: According to the Mononobe–Okabe method that used to calculate seismic active earth pressure, incorporating the inertia forces exerted by earthquakes on the retained soil. The seismic coefficient is set at $\alpha h = 0.10$, resulting in: $\theta = \tan^{-1}(0.10) = 5.71°$.

For saturated backfill with γ=20 kN/m3)

The seismic catarrh pressure coefficient (Ka) is: giving: Ka,seismic = 0.45 is for this condition. The resultant active earth pressure (Ph) is calculated as:

Substitute all values: Ph = $\frac{1}{2}K a \gamma H^2 = \frac{1}{2} \times 0.45m \times 20KN/m3 \times (4m)$ ^2 = 72KN/m. The resultant force acts at a height of H/3:H/3=1.33 m above the base of H/3 =4/3 = 1.33m .Where, Ka = coefficient of earth pressure, H= wall height and γ is unit weight of soil and Acts at H/3 = 1.33 m above base.

2. Hydrostatic pressure (saturated backfill)(Pw)

Under saturated backfill conditions without drainage, hydrostatic water pressure develops behind the wall and acts as an additional lateral load. The hydrostatic pressure is calculated as: It is water pressure If, there is no drainage, it acts worst pressure at the behind of the wall. This pressure is computed as: $Pw = ½ \times \gamma w \times H^2$, Pw = ½ × 10 × 16 = 80 kN/m Acts at H/3 = 1.33 m. Where, γw is unit weight of water

3. Surcharge (Ps): Surcharge represents additional load from traffic or access above the backfill. If any, assume 10kN/m² for access. Ps = Ka × q × H = 0.45 × 10 × 4.0 = 18 kN/m and Acts at H/2 = 2.0 m

4. Total horizontal force (ΣH): This represents the sum of all horizontal pressures act on the retaining wall.

ΣH = 72 + 80 + 18 = 170 kN/m, this is the sum of soil water and surcharge forces.

5. Total overturning moment (ΣMot): This is total moment causing the wall to rotate about its toe due to lateral forces.Mot = (72 × 1.33) + (80 × 1.33) + (18 × 2.0)=Mot = 95.76 + 106.4 + 36.0 = 238.16 kN·m/m.

6.Improvement with drainage: Based on (Berg et al., 2009) guide proper drainage systems such as weep holes and granular drainage backfill significantly reduce hydrostatic pressure behind retaining walls. Therefore, under drained conditions, the hydrostatic water pressure is neglected.

7. Effect of Drainage Improvement: With proper drainage provisions, only the active earth pressure and surcharge pressure remain: With proper drainage provisions, only the active earth pressure and surcharge pressure remain: ΣH (without water) = 72 + 18 = 90.0 kN/m, it is reduced by 47%.Similarly, the overturning moment becomes:ΣMot (without water) = 95.76 + 36.0 = 131.8 kN·m/m.This demonstrates that adequate drainage substantially improves the overall stability and safety of the retaining wall.

Step 3: Vertical Forces (ΣV) and Stabilizing Moment (ΣMstab)

According to the principles established by Bowless(1996), the vertical forces in this design ensure stability against overturning by producing resisting moments that counterbalance the lateral earth pressures exerted on the retaining wall. Those forces are: Stem self-weight, Base slab weight, Backfill weight, Surcharge load and Shear key weight forces computed using from data table (4.18).

Table 4.58: Vertical Loads and Stabilizing Moments

Component	Formula	Calculation	Force (kN/m)	Lever arm (m)	Moment (kN·m/m)
Stem	$\gamma_c \times t_s \times H$	0.35×4.0×25	35	1.25	43.75
Base stem	$\gamma_c \times B \times t_b$	3.5×0.45×25	39.4	1.75	68.9
Backfill on heel	$\gamma s \times A_{bf}$	2.0×4.0×20	160	2.5	400
Surcharge on heel	$q \times A_q$	2.0×10	20	2.5	50.0
Shear key	$\gamma_c \times b_{sk} \times d_{sk}$	0.75×0.4×25	7.5	1.25	9.4
ΣV	-	-	261.9	-	-
ΣMstab	-	--	-	-	572.08

Step.4: Stability analysis with drainage

Based on the Drainage (Das, 2011) guide line,this segment examines the stability of the retaining wall in drained conditions, taking into account the failure modes of overturning and sliding.

1. Overturning: FSoverturning = ΣMstab / ΣMot = 572.1 / 131.8 = 4.34 ≥ 2.0 Ok!
2. Sliding with shear key and without foundation embodiment

According to Terzaghi, Peck & Mesri (1996), the resistance to sliding is achieved through base friction and the passive resistance generated by the shear key.

a. Passive pressure coefficient (Kp): $Kp = \frac{(1 + sin\varphi)}{(1 - sin\varphi)} = \frac{(1 + 0.5)}{(1 - 0.5)} = 3.0$

b. Passive Force at Shear Key(Pp) at d = 0.75m: $Pp = \frac{1}{2} Ka \gamma d^2 = ½ \times 3.0 \times 20 \times 0.75^2 = 16.9$ kN/m

c. Sliding Factor of Safety (FSsliding) = $\frac{(\mu \times \Sigma V + Pp)}{\Sigma H}$, when μ = 0.55 for concrete at weathered basalt. = $\frac{((0.55 \times 261.9 + 16.9)}{90} = 1.79 \geq 1.5$ Ok.

3. Sliding Stability (With Foundation Embedment)

As stated by Bowles (1996), extra resistance is generated as a result of the passive earth pressure acting on the embedded foundation. .

With foundation depth Df = 1.2 m

a.Passive Resistance :$P_{front} = ½ \times Kp \times \gamma sat \times D_f^2 = P_{front} = ½ \times 3.0 \times 20 \times (1.2)^2 = 43.2$ kN/m

b. Sliding Factor of Safety ($FS_{sliding}$): $FS_{sliding} = \frac{(\mu \Sigma V+Pp+Pfront)}{\Sigma H} = \frac{((0.55 \times 261.9 + 16.9 + 43.2)}{90}$ =2.27≥1.5 OK.

The retaining wall meets all stability criteria when drained. The factors of safety against both overturning and sliding surpass the minimum design thresholds, thereby affirming the structure's safety and stability under the specified loading conditions.

Step 5.Base Pressure Analysis

According to Terzaghi (1943), this examination evaluates the distribution of base pressure, the bearing capacity of the soil, and the degree of eccentricity to verify that the resultant force is located within the central third, thereby avoiding tensile stress and ensuring the foundation operates safely.

a. Resultant location: ΣMnet = ΣMstab - ΣMot = 57.1 - 131.8 = 440.3 kN·m/m `

and Resultant from toe= 440.3/261.9=1.68m.

b. Eccentricity e = b/2-(ΣMnet / ΣV) = 2.0 - (440.3 / 261.9) = 1.75 – 1.68 = 0.07 m (within middle third, since b/6=0.583 m).

c. Base Pressure Distributionat toe: = Pmax = $\frac{\Sigma V}{b}$* (1 +$\frac{6e}{b}$)=74.8*(1+0.12) = 74.8*1.12 = 83.8 kpa

Minimum base pressure at toe and Pmin =$\frac{\Sigma V}{b}$* (1 - $\frac{6e}{b}$) = 74.8 × 0.88 = 65.8 kPa no tension.

d. Bearing capacity with foundation depth

Using the Kisan et al.(1981),about the allowable bearing pressure with foundation depth guide line use the value of Presumptive safe bearing capacity at ground level as 150KN/M3 with depth of foundation below ground level(Df=1.2m),the above Max base pressure at toe(83.8KPa). qa = 150 + (γ × Df) = 150 + (20 × 1.2) = 174 kPa = 83.8kPa ≤ 174 kPa Ok. Were: qa is allowable bearing capacity of soil (kPa), γ Unit weight of soil (20 kN/m³).

Step6. Structural design and Reinforcement: This design is done carried out in accordance with BS 8110-1(1997), EN (1992-1-1:2004) and ACI 318-14.)

i. Steam reinforcement

A. Main Vertical Reinforcement: Bending moment at base of stem = 131.8 kN·m/m, Stem thickness at base = 500 mm,Cover = 50 mm and assume Φ16 bar and Effective depth (d) = Total thickness - Cover - (Bar diameter / 2),d = 442 mm (500 mm thickness – 50 mm cover – 8 mm bar). Required steel area: As = M / (0.87 × fy × 0.9 × d) = 131.8×10⁶ / (0.87 × 415 × 0.9 × 442) ≈918 mm²/m and Number of bar per meter = 1000/200=5 number of bars.

Provided reinforcement: As = 5× (π× 16^2/4) = 5*201mm^2 = 1005 mm^2/provide Φ16 @ 200 mm c/c (As = 1005 mm²/m) on back face

B. Horizontal Distribution Reinforcement: Install Φ12 bars at 250 mm center-to-center spacing on both surfaces. This meets the minimum reinforcement standards and mitigates cracking as per ACI 530-13.

C. Stem – Shear Check: Vstem = 90.0 kN/m (drained case)

Design shear strength of concrete (C25/30): τc = 0.35 MPa, (BS 8110-1:1997, Table 3.8), Vc = 0.35 × 1000 × 442 = 154.7 kN/m ≥ 90.0 kN/m Ok! No shear reinforcement needed.

ii. Base Slab Reinforcement

a. Toe Slab (Bottom Reinforcement) :Max bearing pressure at toe = 83.6 kP and Toe length= 1.0m

Bending moment: Mtoe = $(P_{max} \times toe^2 / 2) = 83.6 \times (1.0)^2 / 2 = 41.8$ kN·m/m

Effective depth: d= 450-50-6 (assume Φ12 bar) and d=450-56= 394mm

Required steel: $As = (41.8 \times 10^6) / (0.87 \times 415 \times 0.9 \times 394) = 41.8\times10^6 / (128{,}000) = 326.49 \approx 327$ mm²/m

Number of bar per meter= 1000/250= 4 number of bars

Provided reinforcement:Then steel area per meter $As = 4\times (\pi\times 12^2/4) = 4*113mm^2 = 452\ mm^2/m$

Provide Φ12 @ 250 mm c/c (As = 452 mm²/m)

b. Base Slab – Heel top Reinforcement: Heel length = 2.0 m,Backfill pressure at base of stem = $\gamma sat \times H$ 20 × 4.0 = 80 kPa , Surcharge = 10 kPa, Moment at stem face (simplified uniform pressure assumption) Mheel = (80 × 2.0 × 1.0) + (10 × 2.0 × 1.0) = 160 + 20 = 180.0 kN·m/m.

Remark: Actual trapezoidal distribution gives slightly lower moment.

Cover= 40mm.Assume Φ20 bar,d = 450 - 40 - 10 = 400 mm, $As = (180.0 \times 10^6) / (0.87 \times 415 \times 0.9 \times 400)$, $As = 180.0\times10^6 / (0.87 \times 415 \times 360)$, $As = 180.0\times10^6 / (129{,}978) \approx 1385$ mm²/m, &Number of bar per meter =1000/200= 5 number of bars. Then steel area per meter $As = 5\times (\pi\times 20^2/4) = 1570\ mm^2/m$.

Provide Φ20 @ 200 mm c/c (As = 1570 mm²/m) top reinforcement

Provide Φ20 @ 150 mm c/c (As = 2095 mm²/m) top reinforcement safer.

iv. Shear Key Reinforcement

According to soil mechanics in engineering practice, provide Φ12 bars at 200 mm center-to-center on both Sides and Φ8 stirrups at 300 mm C-to-C. This ensures sufficient resistance to sliding and maintains Structural integrity.

Step6. Foundation and Construction of the retaining wall:The foundation and construction details of the Reinforced concrete cantilever retaining wall was designed following standard geotechnical and structural engineering practices to ensure safety against settlement, scour, and structural failure.Proper excavation, foundation preparation, concrete cover, and controlled backfilling were applied to enhance the stability, durability, and long-term performance of the structure.

Table 4.59: Foundation and Construction Details

Item	Value	Reference
Foundation depth (Df)	1.2m below finished grade (1.5m at toe)	BS 6031:2009
Total excavation depth	1.65 m (1.2 m + 0.45 m base)	-
Lean concrete	0.10 m C10 under entire base	Standard construction
Concrete cover – bottom/back	50 mm	ACI 318-14
Concrete cover – other faces	40 mm	EN 1992-1-1
Backfill compaction	95% MDD	BS 6031:2009

Step 7.Scour Protection (Due to 12.4° Weir Deviation)

The 12.4° weir axis deviation causes uneven flow concentration, increasing flow velocity and the risk of local scour near the retaining wall toe. Therefore, suitable scour protection measures were provided to enhance foundation safety and structural durability.

Table 4.60: Scour Protection Measures for Weir Deviation (12.4°)

Measure	Specification
Riprap apron at toe	1.5 m wide × 0.5 m thick
Riprap stone size	150–300 mm
Filter layer	150 mm coarse sand
Foundation depth in scour zone	Increase to 1.5 at left toe

Table 4.61: Summary of Final Design Dimensions

Parameter	Value
Total base width (b)	3.5 m
Toe length	1.0 m
Heel length	2.0 m
Base slab thickness	0.45 m
Stem thickness at base	0.50 m
Stem thickness at top	0.20 m
Shear key depth	0.75 m
Shear key width	0.4 m
Foundation depth	1.2 m

Table 8.62: Stability Analysis Summary

Check	Value	Requirement	Status
FS overturning	4.34	≥ 2.0	OK!
FS sliding (with key)	1.79	≥ 1.5	OK!
FS sliding (with embedment)	2.27	≥ 1.5	OK!
Max bearing pressure	83.8 kPa	≤ 174 kPa	OK!
Eccentricity	0.07 m	≤ b/6 = 0.583 m	OK!

Step 8: Bill of Quantity and Engineering cost estimates Option-2 (RC- wall)

The bill of quantity and cost estimate for the reinforced concrete cantilever retaining wall were prepared based on the final design dimensions, required materials, labour, and construction activities, including excavation, concrete works, reinforcement, drainage, backfilling, and scour protection.

Table 4.63: Detailed Bill of Quantities and Cost Estimate for Reinforced Concrete Retaining W.

Item	Description	Unit	Quantity	Unit price (birr)	Total amount (birr)
1	Site clearing and removing top soil (6m width×30m length)	m²	180.00	106.00	19,080.00
2	Excavation (3.5m width×1.65m depth) and toe trench 0.6m×0.6m×1m	m³	184.05	998.00	183,681.90
3	Formwork	m²	297.00	2,450.00	727,650.00
4	0.1m thick & 3.5m width Lean Concrete C-10 under entire base and 0.6m×0.1m×1m under toe trench	m³	12.30	12,970.00	159,531.00
5	0.45m thick Reinforced Concrete Base Slab (C-25/30)	m³	47.25	20,393.00	963,569.25
	Reinforced Concrete Stem (avg 0.375m thick × 4m height)	m³	45.00	20,393.00	917,685.00
6	Reinforced Concrete Shear Key (0.4m width×0.75m depth)	m³	9.00	20,393.00	183,537.00
7	Reinforcement – Base slab bottom (Φ12 @ 250 c/c)	kg	106.45	342.00	36,404.53
8	Reinforcement – Base slab top (Φ20 @ 150 c/c)	kg	493.37	342.00	168,733.40
9	Reinforcement – Shear key (Φ12 @ 200 c/c each face + Φ8 @ 300 stirrups)	kg	259.50	342.00	88,749.00
10	Reinforcement – Stem vertical (Φ16 @ 200 c/c back face)	kg	946.71	342.00	323,774.82
11	Reinforcement – Stem horizontal (Φ12 @ 250 c/c both faces)	kg	212.89	342.00	72,809.06
12	Backfill (saturated, 95% MDD), heel length 2.0m and height 4m	m³	240.00	1,200.00	288,000.00
13	Granular drainage layer (300 mm thick behind stem) with around 4m	m³	36.00	3,200.00	115,200.00
14	Weep holes (75 mm dia @ 1.5 m c/c)	No.	20.00	225.00	4,500.00
15	Riprap scour protection (1.5 m wide × 0.5 m thick)	m³	22.50	3,200.00	72,000.00
16	Filter layer (200 mm coarse sand + geotextile), 1.5 width	m²	45.00	455.00	20,475.00
Total amount in birr before Vat 15%					**4,345,379.96**
Vat 15%					**651,806.99**
Total amount in birr with Vat 15%					**4,997,186.96**
Contigency 10% in birr					**499,718.70**
Grand Total in birr					**5,496,905.65**

Step 9: Work schedule in 8 hour working day for R.C Retaining wall

The construction schedule for the reinforced concrete retaining wall was prepared based on normal site conditions and an 8-hour working day, covering all major activities from site clearing to scour protection.

Table 4.64: Construction Work Schedule for RC Retaining Wall

Activity	Days
1. Clearing and removing	2
2. Excavation	3
3. Lean concrete	1
4. Base slab reinforcement	2
5. Base slab concrete	1.5
6. Stem and shear key reinforcement	3
7. Stem and shear key formwork	3
8. Stem and shear key concrete	1.5
9. Backfill and Drainage	2
10. Weep holes	1
11. Scour protection	1
Total in Day	21

Step 10: Comparison of Option 1 and Option 2

Table 4.44 presents a comparative evaluation of the two retaining wall options based on key structural, hydraulic, and durability parameters.

Table 4.65: Compering of the two options using best parameters

Parameter	Option-1 (Masonry)	Option-2 (RC)
Base width	3.5 m	3.5 m
Shear key depth	0.75 m	0.75 m
FS overturning	4.54	4.34
FS sliding	2	1.79
Max base pressure	109.2 kPa	83.8 kPa
Toe length	0.6 m	1.0 m
Heel length	2.3 m	2.0 m
Stem thickness at base	0.60 m	0.50 m
Drainage requirement	500 mm granular + waterproofing	300 mm granular
Scour protection	2.0 m × 0.6 m riprap	1.5 m × 0.5 m riprap
Foundation depth	1.5 m (scour zone)	1.2 m (1.5 m at toe)
Seismic performance	Poor (brittle)	Good (ductile)
Long-term durability	30–40 years	50–75 years
Recommendation	Acceptable with extra measures	Recommended

Step11: Conclusion

The masonry retaining wall is acceptable under improved conditions, provided that key safety measures are implemented, including: Base width = 3.5 m ,Shear key depth = 0.75 m ,Friction coefficient (μ) = 0.55 ,Foundation depth = 1.5 m in scour zones ,Enlarged scour protection (2.0 m × 0.6 m riprap) ,Reinforced concrete base and shear key ,Enhanced drainage system (500 mm granular layer + waterproofing)

Option 2 (Reinforced Concrete Wall)The reinforced concrete cantilever wall is preferred due to its: Lower sensitivity to drainage failure ,Reduced maintenance requirements ,Simpler and faster construction ,Better seismic performance (ductile behaviour) ,Longer service life (50+ years) Overall: Option 2 is the most suitable and reliable solution for long-term performance and safety under the given site conditions.

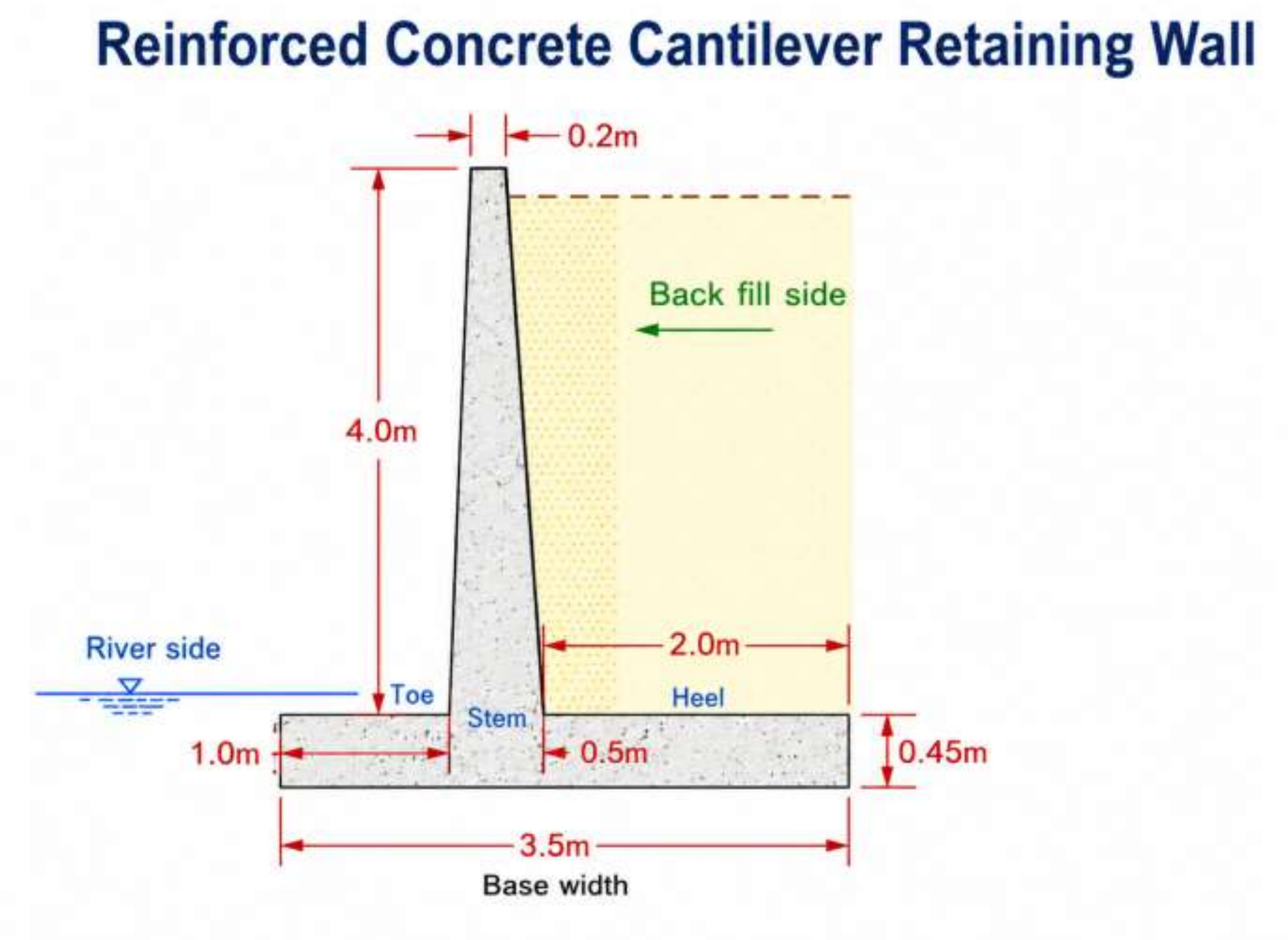


Figure: Designed concrete Reinforced retaining wall

4.6.3 Farmers' Water Management Practices and Irrigation Scheduling Mitigation Strategies

4.6.3. 1 Observed Results and Problems

The study shows inefficient irrigation practices in the scheme. About 53.23% of farmers irrigate based on water availability, while 69.35% over-irrigate for more than 4 hours per application. There is no formal irrigation scheduling system, and 79.03% of farmers lack technical awareness, leading to poor timing, water wastage, and low efficiency.

4.6.3.3 Mitigation Strategies

To improve farmers' water management practices and irrigation efficiency, the following integrated measures are proposed:

(1).Selected Suitable Crops for Karfe: According to FAO-56 guidelines Allen et al.(1998),including soil, climate, water availability, irrigation compatibility, and economic value, wheat was identified as the most suitable crop for the Karfe SSI scheme, followed by onion, potato, cabbage, and tomato. However, all five crops are suitable for cultivation in the scheme.

(2).Suitable surface irrigation method selection.

The most suitable surface irrigation method was selected using the GPA technique, which evaluated physical, agronomic, and economic factors. Each method was scored on a 0–5 scale, and the method with the highest average score was selected(Allen et al., 1998).

Table 4.66: using GPA method selecting surface irrigation method for karfe scheme

Sub-Factors	Surface irrigation water application methods			
	Flood irrigation	Basin irrigation	Border irrigation	Furrow irrigation
Soil Suitability (Vertisol)	1	3	4	5
Slope moderate flat	3	1	5	5
Water Scarcity Adaptation	1	3	4	4
Water Use Efficiency	1	3	4	4
Crop Suitability	3	2	4	5
Labour Requirement	2	3	3	4
Cost Effectiveness	5	5	4	4
Irrigation Control	1	3	4	4
Waterlogging Risk	1	1	3	4
Field Adaptability	3	2	4	5
Total Score	21	26	39	44
GPA (Average)	2.1	2.6	3.9	4.4

Based On the GPA result for flood, basin border and furrow irrigation values 2.1, 2.6, 3.9 and 4.4 respectively. This indicates furrow irrigation method is the first suitable method followed by border irrigation. The basin and flood irrigation systems are lest due to their inappropriate.

Therefore: in order to improve the water management efficiency scheme focused on furrow irrigation method with appropriate field levelling, bund strengthening and scheduling activities

(3) Proposed management

As modern irrigation the system the all crop management practices must be applied based on selected furrow irrigation method, crop spacing, furrow spacing furrow depth. Furrow spacing, depth, and length vary by crop: tomato (75–100 cm, 20–30 cm, 30–60 m), onion (20–30 cm, 10–20 cm, 30–50 m), cabbage (50–70 cm, 20–30 cm, 40–70 m), and wheat (20–30 cm, 10–15 cm, 60–120 m), depending on crop water need and Vertisol soil conditions.

Based on FAO (1985), guidelines, furrow irrigation is the most suitable method for tomato, onion, and cabbage due to its efficient water control and compatibility with Vertisol soils. Furrow dimensions should be adjusted according to crop spacing, root depth, and soil characteristics. For wheat, border irrigation is preferred because it provides uniform water distribution for closely spaced crops, although furrow irrigation may also be used where conditions permit.

(4).Water Management at the field

Field observations showed that farmers often apply water at the head of the furrow and allow it to flow continuously for long periods without proper control, resulting in poor irrigation uniformity and significant water losses. Therefore, farmers should be trained on efficient water management practices, including reducing irrigation duration (from over 4 hours to about 1.5–3 hours), improving furrow design, and ensuring proper land levelling. Additional measures such as mulching, improved bund construction, better field layout, and soil moisture-based irrigation scheduling can further reduce water losses and enhance irrigation efficiency.

(5).Farmer Training and Extension Program

Farmer training and experience sharing are essential to improve irrigation management, water use efficiency, and overall system performance. As stated by FAO (2018) reported that farmer training and participatory management improve irrigation efficiency, water distribution, and the sustainability of irrigation schemes.

5. Conclusion and Recommendation

5.1 Conclusion

This study evaluated the performance of the Karfe irrigation scheme which located in the Adaa Woreda,Karfe keble , East Shoa Zone of the Oromia region in central Ethiopia. The assessment conducted on water supply adequacy, equity, reliability, conveyance efficiency and distribution uniformity, structural integrity, soil properties, and the irrigation practices of farmers within the command area. The evaluation was carried out using field measurements, soil analysis, observations, interviews, questionnaires, and secondary data, and results were compared with standard performance indicators to identify the main technical, operational, structural, and institutional constraints affecting the scheme's performance and sustainability.

Soil analysis showed that the command area is dominated by clay (Vertisol-type) soil, with an average bulk density of 1.11 g/cm^3, field capacity of 0.39m^3/m^3, permanent wilting point of 0.24 m^3/m^3, and available water content of 0.15m^3/m^3. These soil characteristics are suitable for agriculture due to high water storage capacity, but they require careful irrigation management because of low infiltration rates and limited root penetration.The field irrigation performance results indicated that application efficiency (Ea) ranged from 49.65% at the head, 53.81% at the middle, and 62.42% at the tail, with an overall average of 54.82%. Storage efficiency (Es) was relatively higher, varying from 84.49% to 97.25%, with an average of 89.10%, indicating moderate performance but uneven water application across the scheme.

Water supply adequacy and reliability analysis showed spatial variability along the canal system. The Supply Adequacy Ratio (SAR) was 1.21 at the head, 1.09 at the middle, and 0.93 at the tail. The Relative Water Supply (RWS) values of 4.40, 1.24, and 0.71 for head, middle, and tail respectively indicate excess supply upstream and deficit conditions downstream. The Reliability Index (RI) was 100% at the head and middle sections but dropped to 50% at the tail, with deficit ratios reaching 23% in February and 29% in March. These results confirm inequitable water distribution within the scheme.

The conveyance performance results showed that conveyance efficiency (Ec) was 92.39% at the head, 92.16% at the middle, and 90.91% at the tail. However, the overall conveyance efficiency was 76.09%, with total conveyance losses of 23.91%. These losses were mainly due to seepage, sediment deposition, vegetation growth, and unlined canal sections.

Equity analysis further showed declining performance along the system, with delivery performance ratio (DPR) decreasing from 0.64 at the head to 0.51 at the tail, and an overall mean of 0.58, indicating only 58% of the designed discharge is delivered to the field.

Structural assessment revealed that the irrigation infrastructure is in poor condition, with a Structural Condition Index (SCI) of 2.36 and Infrastructure Effectiveness Index (EI) of 33.93%. Sedimentation effects were moderate (SSI) 24%, with serious deposition in some canal sections. Hydraulic and stability analysis also indicated structural problems, including weir misalignment, insufficient hydraulic jump length, and low safety factors for sliding (1.45) and overturning (1.88), leading to retaining wall instability and partial failure.

Farmers' irrigation practices were found to be inefficient and largely traditional. Irrigation scheduling is mainly based on fixed rotation and water availability, do not irrigate based on the crop water requirements. Most farmers apply water for more than 4 hours due to the long irrigation interval; field creates cracking, with low awareness and limited training. Institutional support is weak, conflicts are frequent, and maintenance is mostly done individually rather than through organized systems. The Farmer Management Index (FMI) of 30% confirms poor irrigation management.

Finally, the Overall Performance Index (OPI) of the scheme is 56%, which falls within the moderate performance category (50–70%). The sectional scores show water supply (0.60), conveyance (0.70), structures (0.41), farmer and institutional practices (0.47), and application and storage efficiency (0.61). This indicates that although conveyance performance is relatively better, the overall system is constrained by poor structural condition and weak farmer–institutional management, which significantly limits efficiency and long-term sustainability.

Overall, the study concludes that the suboptimal performance of the Karfe irrigation scheme results from a mix of technical shortcomings, weak operation and maintenance practices, limited institutional capacity, deterioration of hydraulic structures, unequal water distribution, and low farmer awareness of proper irrigation management. Although the scheme is still operational, its sustainability and productivity are at risk unless timely technical rehabilitation and effective management improvements are introduced.

5.2 Recommendations

Based on the results of this research, the following suggestions are made to enhance the technical performance, efficiency of water distribution, structural integrity, institutional management, and long-term sustainability of the Karfe Small-Scale Irrigation Scheme.

5.2.1Technical and Structural Recommendations

- Rehabilitate damaged structures including the two head regulators,
- Reconstruct the left failed retaining wall using reinforced concrete,
- Delisting the two non-functional under sluices gates, maintain off-takes gates.
- Complete unfinished right side unlined main can in to lines
- Line the damaged section of the main canal
- Carry out regular delisting and weed removal before each irrigation season
- Be construct drainage structures and accesses roads parallel to the main can
- Built water and soil conservation structures to reduce impact of canals

5.2.2 Water Management and Operational Recommendations

- Irrigate based on the crop water requirement & irrigation scheduling instead of fixed rotation.
- Supply based on the area coverage in simple rotation to reduce head–tail inequality.
- Promote basic land levelling at farm level to reduce uneven application and water loss.
- Implement locally agreed rules through WUA to reduce illegal water abstraction.
- Use simple field observations for routine monitoring to reduce losses due to over irrigation.

5.2.3 Institutional and Capacity Building Recommendations

- Strengthen the WUA to manage water distribution and maintenance effectively.
- Introduce regular farmer training on irrigation timing, crop water needs, and efficient water use.
- Encourage participatory irrigation management to farmers take responsibility
- Establish a simple shared maintenance system between farmers and irrigation officials to prevent.
- Train about the use of solar pumps instead of diesel pumps to be cost effective

5.2.4: Future Research Recommendations

- ❖ Assess climate variability impacts on irrigation water reliability.
- ❖ Evaluate low-cost rehabilitation options suitable for small-scale irrigation schemes**.**

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7. Appendix

7.1Appendix A: Hydraulic

Table A.1: Four-month average flow of the Right Main Canal (R-MC) with losses and conveyance efficiency

Month	Section	Chainage	Length (km)	Initial Q (lps)	Final Q (lps)	Q Loss (lps)	Loss Rate (lps/km)	Con. Efficiency (%)	Canal Type
January	Head	0+000 –0+940	0.9	40.0	37.0	3.0	3.2	92.5	Lined
	Middle	0+940 – 1+870	0.9	37.0	34.0	3.0	3.2	91.9	Lined
	Tail	1+870 – 2+230	0.4	34.0	33.0	1.0	2.8	97.1	Lined
	Tail	2+230 – 2+810	0.6	33.0	30.0	3.0	5.2	90.9	Earthen
	Total	0+000 – 2+810	2.8	40.0	30.0	10.0	3.6	75.0	all
February	Head	0+000 – 0+940	0.9	37.0	33.0	4.0	4.3	89.2	Lined
	Middle	0+940 – 1+870	0.9	33.0	30.0	3.0	3.2	90.9	Lined
	Tail	1+870 – 2+230	0.4	30.0	29.0	1.0	2.8	96.7	Lined
	Tail	2+230 – 2+810	0.6	29.0	26.0	3.0	5.2	89.7	Earthen
	Total	0+000 – 2+810	2.8	37.0	26.0	11.0	3.9	70.3	All
March	Head	0+000 – 0+940	0.9	34.0	31.0	3.0	3.2	91.2	Lined
	Middle	0+940 – 1+870	0.9	31.0	29.0	2.0	2.2	93.6	Lined
	Tail	1+870 – 2+230	0.4	29.0	28.0	1.0	2.8	96.6	Lined
	Tail	2+230 – 2+810	0.6	28.0	25.0	3.0	5.2	89.3	Earthen
	Total	0+000 – 2+810	2.8	34.0	25.0	9.0	3.2	73.5	All
April	Head	0+000 – 0+940	0.9	35.0	31.0	4.0	4.3	88.6	Lined
	Middle	0+940 – 1+870	0.9	31.0	27.0	4.0	4.3	87.1	Lined
	Tail	1+870 – 2+230	0.4	27.0	26.0	1.0	2.8	96.3	Lined
	Tail	2+230 – 2+810	0.6	26.0	23.0	3.0	5.2	88.5	Earthen
	Total	0+000 – 2+810	2.8	35.0	23.0	12.0	4.3	65.7	All

Table A.2: Four-month average flow of the Left- Main Canal (L-MC) with losses and conveyance efficiency

Month	Section	Chainage	Length (km)	Initial Q (lps)	Final Q (lps)	Q Loss (lps)	Loss Rate (lps/km)	Conveyance Efficiency (%)	Canal Type
January	Head	0+000 – 0+500	0.5	35.0	33	2.0	4.0	94.29	Lined
	Middle	0+500 – 1+000	0.5	33.0	31	2.0	4.0	93.94	Lined
	Tail	1+000 – 1+500	0.5	31.0	28	3.0	6.0	90.32	Earthen
	Total	0+000 – 1+500	1.5	35.0	28	7.0	4.7	80.00	All
February	Head	0+000 – 0+500	0.5	33.0	31	2.0	4.0	93.94	Lined
	Middle	0+500 – 1+000	0.5	31.0	29	2.0	4.0	93.55	Lined
	Tail	1+000 – 1+500	0.5	29.0	27	2.0	4.0	93.10	Lined
	Total	0+000 – 1+500	1.5	33.0	27	6.0	4.0	81.82	All
March	Head	0+000 – 0+500	0.5	30.0	29	1.0	2.0	96.67	Lined
	Middle	0+500 – 1+000	0.5	29.0	27	2.0	4.0	93.10	Lined
	Tail	1+000 – 1+500	0.5	27.0	25	2.0	4.0	92.59	Lined
	Total	0+000 – 1+500	1.5	30.0	25	5.0	3.3	83.33	All
April	Head	0+000 – 0+500	0.5	32.0	30	2.0	4.0	93.75	Lined
	Middle	0+500 – 1+000	0.5	30.0	28	2.0	4.0	93.33	Lined
	Tail	1+000 – 1+500	0.5	28.0	26	2.0	4.0	92.86	Lined
	Total	0+000 – 1+500	1.5	32.0	26	6.0	4.0	81.25	All

7.2 Appendix B: Climatic Data

Table B.1:Monthly climatic paramatres rain fall and Refernced Evapotransparation(ETo) data

Months	Min.T (^{0}C)	Max.T (^{0}C)	RH (%)	Wind S (km/hr)	Sunshine (hr)	Radiation MJ/m²/day	ETo (mm/day)	ETo (mm/month)	RF(mm/month)	Effective RF(mm/month)
Jan	8.6	26.1	54	13.22	7.9	19.3	3.55	106.5	8	0
Feb	11.8	26.8	57	14.92	8.3	21.0	4.02	120.6	34	10.4
Mar	12.8	28.4	51	16.96	8.5	22.4	4.55	136.5	52	21.2
Apr	12.8	27.7	55	18.76	8.1	21.9	4.49	134.7	65	29.0
May	12.8	28.3	48	19.6	7.7	20.8	4.45	133.5	73	34.4
Jun	12.3	26.9	59	20.19	6.5	18.7	3.84	115.2	107	61.6
Jul	13.3	24.4	69	19.62	5.4	17.1	3.35	100.5	178	118.4
Aug	13.1	23.9	72	19.03	5.4	17.5	3.33	99.9	230	160
Sep	12.3	24.9	71	18.34	6.3	18.9	3.52	105.6	99	55.2
Oct	9.8	26.4	49	15.32	8.3	21.2	4.11	123.3	14	0
Nov	8.6	26.5	46	13.33	8.9	20.9	4.19	125.7	3	0
Dec	8.3	25.4	43	12.47	8.4	19.50	3.73	111.9	2	0
Mean	11.38	26.31	56.17	16.81	7.48	19.93	3.93	117.90	72.08	490.20

7.3 Appendix Figure

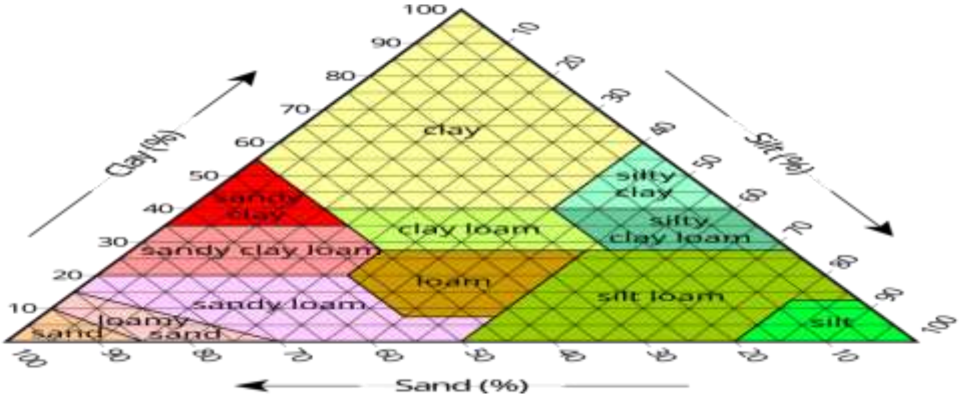

Figure7. 1: Soil Texture Triangle (USDA Classification System)

Figure 7.3: Water losses from the main canal

7.3.1 Household Questionnaire for Irrigation Users

1. Sex
   A. Male B. Female
2. Age
   A. 18–30 years B.31–45 years C. 46–60 years D. above 60 years
3. Educational level
   A. Illiterate B. Primary School C. Secondary School A. above Secondary
4. Farming experience
   A. less than 5 years B.5–10 years C. 11–20 years D. Above 20 years
5. How much your landholding size?
   A. less than 0.5 ha B. 0.5–1.0 ha C. 1–2 ha D. Above 2 ha
6. Who decides irrigation scheduling in the scheme?
   A. Farmers B. Fixed rotational system C. Water Users Association (WUA) D. Kebele administration
7. What criteria do you use to schedule irrigation?
   A. Based on water availability B. Observation of crop leaves and soil moisture
   C. Fixed rotation
8. Are you aware of proper irrigation scheduling practices?
   A. Yes B. No
9. How do you decide when to irrigate?
   A. Based on water availability B. By observing soil dryness
   C. Based on crop water needs D. Fixed schedule
10. How long do you irrigate during one irrigation event?
    A. Less than 2 hours B. 2–4 hours C. Above 4 hours
11. Which irrigation method do you use?
    A. Flood irrigation B. Furrow irrigation C. Border irrigation
12. What type of irrigation technology do you use?
    A. Traditional irrigation system B. Diesel water pump C. Solar pump
13. Do you use water control structures in your farm?
    A. Yes B. No
14. Have you received irrigation-related training?
    A. Yes B. No
15. Do you receive institutional support for irrigation management?
    A. Yes B. No
16. Is there conflict related to irrigation water use in the scheme?
    A. Yes B. No
17. Who mainly resolves irrigation conflicts?
    A. Farmers/WUA B. Kebele administration C. Elders/Committee
18. What are the major causes of conflict in the irrigation scheme?
    A. Water shortage B. Water theft C. Inequity in water distribution
    D. Poor management E. Irrigation scheduling disputes
19. How is maintenance of the irrigation scheme carried out?
    A. Regular routine maintenance B. Occasional
    C. By individual farmers D. Only during emergencies
20. What are the major challenges affecting the irrigation scheme?
    A. Over-irrigation B. Low knowledge of irrigation management C. Poor infrastructure D. Water scarcity

21. What suggestions do you recommend to improve irrigation performance and water management in the scheme? ----------------- --::