Mekelle University

Ethiopian Institute of Technology-Mekelle

Faculty of Civil and Environmental Engineering

MSc in Civil Engineering (Irrigation and Drainage Engineering)

Comparison of Empirical and Numerical Methods for Estimating Seepage Losses in Unlined Irrigation Canals: in Laelay-Wukuro Irrigation Scheme, Eastern Tigray, Northern Ethiopia

By

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A Master's Thesis Submitted to the Faculty of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science (MSc)

In

Civil Engineering (Irrigation and Drainage Engineering)

Main Advisor: Berhane Grum (Ph.D.)

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Board of Examiners' Approval

We, the undersigned members of the Board of Examiners for the final open defense of **Tsegay Tesfay Hagos,** have read and evaluated the thesis entitled **"Comparison of Empirical and Numerical Methods for Estimating Seepage Losses in Unlined Irrigation Canals: in Laelay-Wukuro Irrigation Scheme**, **Eastern Tigray**, **Northern Ethiopia"** and assessed the candidate's performance. We hereby certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, with specialization in Irrigation and Drainage Engineering.

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Declaration

I declare that all information on this thesis entitled **"Comparison of Empirical and Numerical Methods for Estimating Seepage Losses in Irrigation Canals: in Laelay-Wukuro Irrigation Scheme, Eastern Tigray Northern Ethiopia"** is my own work and has been obtained and presented according to the academic rules and ethical conduct under the guidance. I'm also the principal author of this research work.

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Dedication

This thesis manuscript is dedicated to my family: Mother, L/slasie Tewelu, and my wife, Meseret Brhane for their unwavering love, patience, and encouragement, which have been my greatest source of strength and inspiration. I am deeply grateful for their endless and generous support!

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Abstract

Efficient irrigation water management requires accurate estimation of seepage losses, particularly in unlined canals. The objective of this study was to quantify seepage losses and to evaluate the performance of empirical and numerical methods for estimating seepage in unlined irrigation canals**.** The study was conducted in the Laelay Wukro irrigation scheme, Eastern Tigray Northern Ethiopia, during the 2024 irrigation season. Seepage losses were assessed in six unlined secondary canal sections (SC1–SC6) with soil textures ranging from loamy sand to clay loam and hydraulic conductivities between 0.30 and 10.72 cm/hr. The methodology involved field measurement of seepage losses and their comparison with estimates obtained from six empirical equations (Davis–Wilson, Moritz, Molesworth and Yennidunia, Swamee, Ingham, and Muskat) and a numerical model (SEEP/W) implemented in GeoStudio software**.** Model performance was evaluated using statistical indicators including the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), coefficient of residual mass (CRM), percentage average error (PAE), and bias. Results showed that the SEEP/W model provided the closest agreement with measured seepage losses ($R^2 = 0.94$, RMSE = 13.25, MAE = 24.12, CRM = 0.02, PAE = −15.4%, and Bias = −0.69), with an average deviation of 2.6% from observed values. In contrast, empirical methods significantly underestimated seepage losses due to their simplified assumptions. The study concludes that the SEEP/W numerical model is a more reliable and realistic tool for seepage analysis in unlined canals and can support improved canal design, seepage control, and irrigation water management in similar hydrogeological settings.

Key words: Empirical equations; Numerical equation; Seep/w; Irrigation canals; Statistical parameters; Seepage loss

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Abbreviations and Acronyms

FAO	Food and Agriculture Organization
FEM	Finite Element Method
R^2	Coefficient of Determination
CRM	Coefficient of Residual Measure
RMSE	Root Mean Square Error
MAE	Maximum Absolute Error
PAE	Percentage of Average Error
Sc1…Sc6	Secondary canal 1…6
ANCID	Australian National Committee on Irrigation and Drainage
Co-SAERT	Commission of Sustainable Agriculture and Environmental Rehabilitation in Tigray
USDA	United States Department Agriculture
ME	Mean Error
EF	Models Efficiency
MAPA	Mean Absolute Percentage Error
RE	Relative Error

1. Introduction

1.1.General

In irrigation schemes, channels are often used to convey water from reservoirs to agricultural land. In addition, water may also be supplied to meet industrial and urban demands. In most cases, the actual amount of water at the end of the channel is significantly less than the amount that entered channels; the most important cause of the decrease is water seepage losses from the channels (Salmasi & Abraham, 2020).

Irrigation conveyance losses due to seepage in unlined canals can consume a large share of diverted water globally estimated at 10–70% of flows reducing delivery efficiency, with small-scale schemes in Ethiopia often showing 30–43% water loss in conveyance systems, highlighting severe inefficiencies in Africa and Ethiopia that undermine water availability for crops (Davis et al., 2025).

Seepage losses through irrigation channels are a significant concern in many irrigation systems worldwide. Accounting for these losses has become more important with the growing emphasis on improved irrigation water management practices. Knowledge of seepage losses within a delivery system is vital for the equitable distribution of irrigation water, knowing the effectiveness of lining, and planning canal scheduling, design, and preparing an optimal cropping plan (Shaikh & Lee, 2016). Consequently, diagnosing and quantifying seepage from channels is critically important for the protection of water resources, effective surface water and groundwater management, determining the severity of seepage-related loss, and for the assessment of the potential technical and financial benefits of seepage reduction techniques and technologies (Martin & Gates, 2014).

The most prevalent methods used to calculate seepage losses from channels mainly include field experiments, empirical formulas, and numerical methods. Field experiments include the inflow–outflow measurement method, ponding tests, the point-measurement method and the double-ring infiltration test (Zhang et al., 2017). Among these, the first three methods are the most widespread at present. The inflow–outflow method is applied to calculate channel seepage losses by measuring the discharge between the upstream and downstream cross sections of the channel. The importance of inflow-outflow method is that seepage losses can be measured under normal operating conditions of the channel. However, for small amounts of seepage loss, this method produces lower precision, and satisfactory test results are hard to achieve (Zhang et al., 2017). Compared to the inflow–outflow method, measurements results using a ponding test are more accurate. The seepage rate can be used to calculate channel seepage losses during the irrigation season or throughout the year. The significant impediment in using the ponding method is the requirement for a heavy workload with a large number of workers resulting in higher overall costs. Consequently, it is rarely applied to large irrigation channels or channels with various branches and sharp slopes. Therefore, for this research study ponding test was used since irrigation project is small.

Many scholars have conducted research and proposed various empirical formulas for estimating seepage losses. These seepage estimation methods include Davison–Wilson, Kostiakov, Inghaln, Molesworth, and Koski formulas (Mowafy, 2001; Akkuzu, 2012; Han et al., 2021). Overall, these formulas are simple in form and can be applied conveniently. However, the coefficients used in empirical seepage formulas show considerable variability, and the formulas are subject to several constraints, making them applicable mainly under specific conditions. In addition, these formulas involve complex parameters and calculation procedures, which limit their universal applicability. Nevertheless, they remain valuable because they provide quick and practical estimates of canal seepage and are widely reported in the literature. In this study, the empirical formulas were therefore applied as comparative and benchmarking tools, and their results were evaluated against field measurements to assess their reliability under local conditions.

When canal seepage is calculated via the numerical method, appropriate equations and boundary conditions that reflect actual seepage conditions must be selected. Then, based on these conditions, a seepage model can be established. Using numerical methods, excessive volumes of data can be processed in a short time with minimum cost (Karimi & Abrishami, 2015). Therefore, this study discusses numerical assessment of seepage phenomenon considering saturated conditions and assesses the capacity of Seep/W software model in estimating water seepage of unlined secondary channels at Laelay Wukro irrigation scheme.

This thesis estimated canal seepage losses in Laelay Wukro Irrigation scheme through the use of a field experiment, empirical formulas, and numerical methods. The results of the field experiment were utilized as a basis to compare and analyze the measurement results of the other methods. After analyzing these methods and their calculation results, the most appropriate method to calculate seepage losses in canals with different forms and under different conditions was selected to provide a basis for the rational utilization of water resources in the investigated irrigation district.

1.2. Statement of the problem

In many developing regions, particularly in semi-arid environments such as northern Ethiopia, irrigation canals play a critical role in supporting agricultural productivity. However, a substantial portion of diverted water is lost through seepage, especially in unlined earthen canals. These losses not only reduce the conveyance efficiency of irrigation systems but also limit the availability of water for downstream users, contributing to water scarcity and reduced crop yields (Reta et al., 2024).

In the Laelay Wukro irrigation scheme, the secondary canals are unlined, and farmers frequently report inadequate water supply at the tail end of the system. Despite this, a major problem in designing and planning canal system, is determining the actual seepage loss to be used in the calculations. Since experimentally determining seepage loss for use in calculations is time consuming and costly, it is usually taken from literatures or recommendations (Shaliteratureikh et al., 2012). Such generalized formulas may not accurately represent local field conditions, leading to under- or overestimation of seepage losses. Most of the irrigation schemes in Ethiopia are found to work below their expectation. One of the main reasons is the seepage loss variation from the expected (designed) value which ultimately affects the envisioned conveyance efficiency (Eshetu & Alamirew, 2018; Shumye, 2018; Chala, 2024)

As a result, numerous researches were carried out to estimate seepage losses with a minimum of data, using geometrical parameters of irrigation channels or soil characteristics (Bakry & Awad, 1997), empirical relations, and U.S. design directives. However, these formulas are sometimes not suitable for specific areas and therefore need to be calibrated (Akkuzu, 2012). A lot of available studies on seepage measurements indicate variations in the magnitude of losses across different areas, due to the fact seepage is governed by numerous aforementioned factors, predominantly soil texture (Alam & Bhutta, 2004; ANCID, 2003). The literature revealed that losses were mostly measured without taking into account soil texture. If these values are adopted to design the capacity of a hydraulic structure or to plan a schedule for an irrigation scheme without accounting for variables like soil texture, the omission may lead to gross underestimation or overestimation of losses, which may lead to failure of the structure.

To address this problem, there is a need for a site-specific and reliable seepage estimation approach that incorporates the physical, hydraulic, and geological characteristics of the study area. The Seep/W numerical model, which uses finite element analysis to simulate seepage under realistic boundary conditions, provides a potential solution. Therefore, this study aims to evaluate seepage losses in the Laelay Wukro unlined irrigation canal using both empirical and numerical methods, compare their performance against measured field data, and identify the most accurate and applicable method for local conditions.

1.3. Objectives

1.3.1. General objective

The general objective of this research is to evaluate the performance of empirical and numerical methods for estimating seepage losses in Laelay Wukro irrigation channels.

1.3.2. Specific objective

- ✓ To analyze the variability of seepage loss at different sections of unlined canal system.
- ✓ To estimate seepage losses using empirical and numerical methods.
- ✓ To evaluate the performance of empirical and numerical seepage estimation methods using measured seepage data.

1.4. Scope of the study

This study focuses on the estimation and comparison of seepage losses in selected sections of an earthen irrigation canal on Laelay Wukro irrigation scheme, Tigray, Ethiopia using both empirical and numerical methods. Six canal sections (SC1–SC6) were analyzed to evaluate seepage discharge rates predicted by the Davis–Wilson, Moritz, Molesworth and Yennidunia, Swamee, Ingham, and Muskat formulas, as well as a numerical model (Seep/W). The results were compared with measured inflow–outflow data to assess the accuracy and applicability of each method under field conditions. The study aims to identify the most reliable approach for seepage estimation in similar soil and hydraulic conditions, supporting improved canal design and water management practices.

1.5. Limitation of the study

The study is limited to six canal sections representing specific soil and geometric characteristics, which may not fully represent other canal types or environmental conditions. The empirical formulas used are based on generalized assumptions and may not accurately reflect local variations in soil texture, compaction, or seepage path. The numerical modeling (Seep/W) results depend on the accuracy of input parameters such as hydraulic conductivity, boundary conditions, and soil layering, which may introduce uncertainty. The measured seepage losses are also subject to potential errors due to evaporation, infiltration to adjacent areas, and measurement inaccuracies. Additionally, the analysis was conducted under steady-state conditions, and seasonal or operational variations in canal flow were not considered. Since many factors affect seepage rate, it is unusual to measure a consistent seepage value for a given reach of canal. The objective of this study is used to determine an approximate range of seepage loss as related to soil texture and canal size.

1.6. Significance of the study

This study is significant because it provides a comparative evaluation of commonly used empirical and numerical methods for estimating seepage losses an issue that critically affects the efficiency and sustainability of irrigation systems. By identifying the most accurate method under different soil conditions, the research helps irrigation engineers, water resource planners, and researchers select appropriate seepage estimation techniques for similar environments. Furthermore, the study contributes to the optimization of water use, reduction of conveyance losses, and improvement of irrigation efficiency, which are essential for sustainable agricultural water management in regions facing water scarcity.

2. Literature Review

2.1. General

Different factors contribute to various types of channel water losses. While most losses occur under steady flow conditions, some result from temporary or unsteady flow situations. Studies estimate that about one-fourth to one-third of the total water diverted for irrigation is lost during conveyance (Syed et al., 2021). According to records from 46 irrigation projects compiled by the U.S. Bureau of Reclamation, these losses can range from 3% to as high as 86%. It has been suggested that if only one-fifth of the water diverted for irrigation in the United States were lost before reaching users, the resulting seepage volume would amount to 27.2 billion m^3 per year. Retaining this water could potentially allow irrigation of an additional 2.2 million hectares, assuming an annual water requirement of 1220 mm. Experiences from other regions worldwide confirm that seepage significantly affects the availability of water for agricultural expansion, representing a major economic loss when the escaped water cannot be recovered for further use.

An accurate estimation of conveyance water losses from an irrigation scheme is essential for the proper control of the system. Water managers are often under pressure to divert more water to compensate for these losses and to make sure that the users receive water according to their requirements. Therefore, for effective operational planning and management of an irrigation system, reliable forecasting of losses is very important (Hameed et al., 1996). Seepage losses can be determined either through direct measurement or estimation.

2.2.Theoretical aspects of seepage

In irrigation systems, canals are extensively used to transfer water from the reservoir to agricultural land. In most cases, the actual amount of water at the end of the canal is significantly lower than the amount of water entered at the beginning of the canal and one of the most important causes of these losses is water seepage from the canals.

Seepage is usually defined as the slow movement of water through small openings and spaces in the surface of unsaturated soil into or out of a body of surface or subsurface water (Cedergren, 2021). Seepage in canals involves the relatively uniform passage of water through the wetted perimeter of the channel profile often due to poor quality of substrate material. Seepage losses through irrigation water channels are a significant concern in many of the world's irrigation systems. Accounting for seepage losses through a system has become more important with the increasing emphasis on improved irrigation water management practices. Knowledge of these losses in a delivery system is vital for the equitable distribution of irrigation water, knowing the effectiveness of lining, and canal scheduling, design, and preparing an optimal cropping plan (Shaikh & Lee, 2016).

Canal seepage loss occurs when water from the pores of the canal bed and canal slopes infiltrates into the surrounding soil and cannot be utilized for crops during water conveyance and distribution (Zhang et al., 2017).

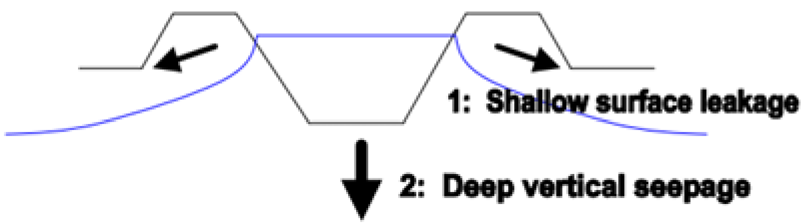


Figure 2-1 Mechanism of seepage from channels (ANCID, 2003)

2.3.Factors affecting seepage in canals

Factors influencing seepage have been reported to include those discussed below (Sun et al., 2023)

2.3.1. Soil characteristics

Two key soil physical properties - soil texture and soil permeability play a major role in determining seepage losses in irrigation canals.

Soil texture refers to the relative proportion of sand, silt, and clay in the soil. The soil texture forms the basic matrix, and the shape of the voids created within this soil matrix depends on the class of soil texture. Therefore, soil texture significantly influences the phases (water and air) contained in the spaces within the soil matrix. A coarse-textured soil will allow water to flow more easily than a fine-textured soil. As a result, soil textural characteristics affect seepage from the canal.

Soil permeability and hydraulic conductivity: Permeability and conductivity are frequently used interchangeably. Permeability in a quantitative term is the characteristic of a pervious medium relating to the readiness with which it transmits fluids. The values of hydraulic conductivity depend on the properties of the fluid as well as those of the soil, and they reflect any interactions of the fluid with the porous medium, such as the swelling of a soil. A soil that has a high porosity and a coarse open texture has a high saturated hydraulic conductivity value. For two soils of the same total porosity, the soil with the smaller pores has the lower conductivity because of the resistance to flow in small pores. Thus, the soil characteristics which affect hydraulic conductivity are the total porosity, the distribution of pore size, and the tortuosity (the pore geometry of the soil).

Seepage is also affected by the hydraulic characteristics of the channel and surrounding area. Hydraulic characteristics of the channel are the channel water level, wetted perimeter of the channel and depth to ground water. Depth to ground water or the difference between the channel water level and the groundwater elevation in the bores close to the channel, defined as net available head is one of the most significant factors in determining the seepage loss rate from a channel (Naranjo et al., 2023). Generally, the seepage rate increases with greater water depth in the channel as well as greater net available head.

The significant depth below the channel bed, affecting the seepage rate is considered to be approximately five times the bed width of the channel. While at a distance of approximately ten times the bed width of the channel, the effect of seepage losses on the original water table elevation is considered to be minimal (ANCID, 2003; Lund et al., 2023).

2.4. Quantifying seepage losses

Water conveyance loss consists mainly of operation losses, evaporation, and seepage into the soil from the sloping surfaces and bed of the canal. The most important of these is seepage. Evaporation loss in irrigation networks is generally not taken into consideration (Xie et al., 1993; ANCID, 2000).

The seepage losses can be determined either by direct measurement or by indirect (estimation) from the relevant hydraulic properties of the soil and the boundary condition, such as depth to groundwater, canal cross-section and water depth. The difficulties in determining the boundary conditions and hydraulic properties of the canal soils make calculating seepage rates complicated (Ahmed et al., 2025). Therefore, researchers and engineers have found it necessary to develop direct measurement methods, various empirical formulas and numerical formulas to estimate seepage losses from irrigation canals.

2.4.1. Direct measurement methods

Literature is reviewed with particular reference to measurement techniques used by various researchers in measuring the seepage losses.

Direct measurement method include the inflow–outflow measurement method, ponding tests, point measurement method, double-ring infiltration test, and permeameter measurement method (Alam & Bhutta, 2004). The first three methods are commonly used at present.

2.4.1.1. Inflow-outflow measurements

The inflow–outflow method, also known as the flowing water-balance method, determines canal seepage by applying a water balance to a defined control volume, typically a canal reach or segment (schematically illustrated in Figure 2.2). In this approach, seepage is treated as an unknown outflow, while all other inflows and outflows such as upstream and downstream discharges, lateral inflows or withdrawals, evaporation, and precipitation are measured during a seepage test. Any change in water storage within the canal reach over the measurement period is also accounted for. Seepage loss is then computed as the residual of the water-balance equation by subtracting the total measured outflows from the total measured inflows, after correcting for storage change.

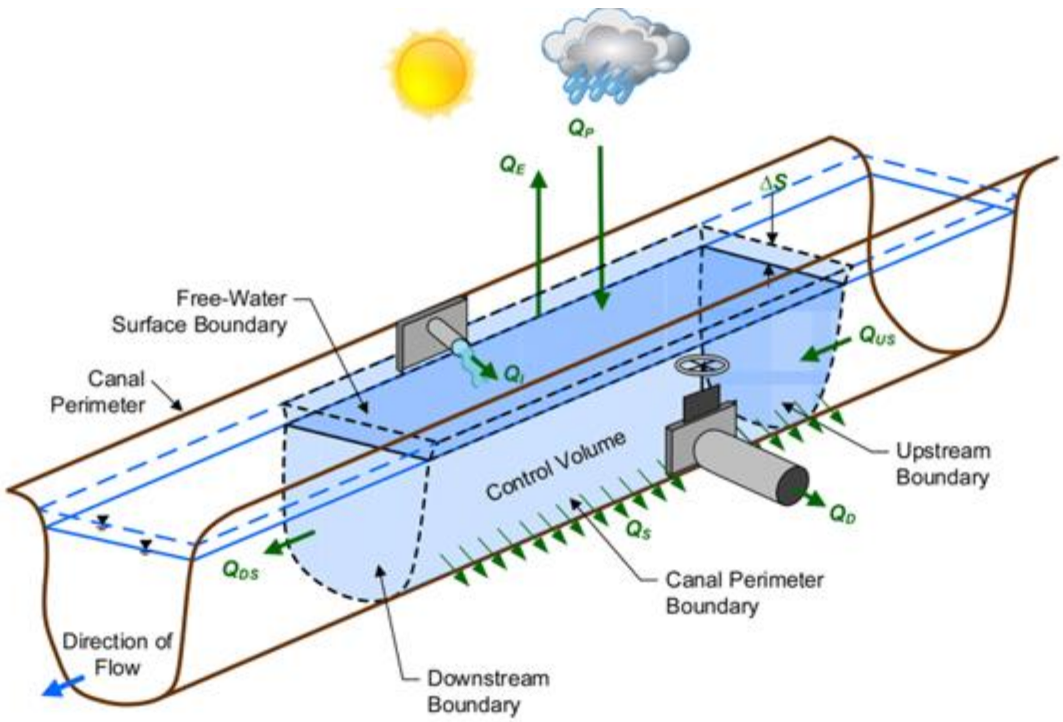


Figure 2-2 Illustration of the inflow-outflow method of measuring seepage along the reach of an irrigation canal (Lund et al., 2023)

As illustrated in Figure 2.2 the inflows along a selected canal reach are the flow rate at the upstream cross section of the reach, Q_{US} [m3/sec]; any inflows to the canal reach from adjacent irrigated lands, Q_I [m3/sec]; and precipitation rate, if any, Q_P [m3/sec]. Outflows are measured at the downstream cross section of the reach, Q_{DS} [m3/sec]; as evaporation from the water surface along the reach, QE [m3/sec]; and as any flow diversions (the turnouts) along the reach length, Q_D [m3/sec]. Any changes in stored volume occurring throughout the seepage measurement, –ΔS/Δt [m3/sec], also must be measured. Seepage rate, Q_S [m3/sec], can then be calculated as. Water balance equation for the reach is,

$$Q_{Us} - Q_{DS} = q_s + q_E + \Delta_{s/}\Delta_t - \ Q_I + \ \ Q_P \qquad [2.1]$$

For all practical purposes, steady, and uniform flow conditions are maintained during the study period, thus, change in storage can be assumed to be zero (Nyagah, 1991).

Nyagah (1991) Stated in his thesis for the considered duration of measurement, q_E, is normally negligible for short reaches of the canal. Hence, seepage loss in l/s/Km is estimated as;

$$S = \frac{Q_{in} - Q_{out}}{L} \quad [2.2]$$

Where, S = seepage rate (1/s/km), L ~ length of canal reach (km).

During measurement the water level in the canal is kept constant to eliminate the effect of canal and bank storage. Webber (1971) observed that in the majority of cases, where relatively long straight channels (of constant cross-section and bed slope) are involved, the flow for the most part is so nearly uniform that the assumption of uniform flow condition is reasonable.

2.4.1.2. Ponding measurements

The ponding test is one of the oldest and most direct field methods for measuring seepage losses from irrigation canals. In this technique, a short reach of canal is isolated by constructing watertight cut-offs or embankments at both ends, and the section is filled with water to a predetermined level. The decline in water level over time corrected for evaporation and precipitation is attributed to seepage through the canal bed and sides, allowing calculation of seepage rates based on changes in volume and wetted area (Hosseinzadeh Asl et al., 2020).

Ponding tests are widely regarded as highly reliable for small segments because they measure seepage under controlled, quasi-static conditions, often yielding more accurate estimates than indirect methods such as inflow–outflow, especially where canal flow is unavailable or difficult to measure (Worstell, 1976). However, the method’s applicability is limited by practical constraints: it requires canal closure during testing, significant water volumes to fill the reach, construction of dams or plugs, and careful correction for factors such as evaporation and rainfall (Alam & Bhutta, 2004).

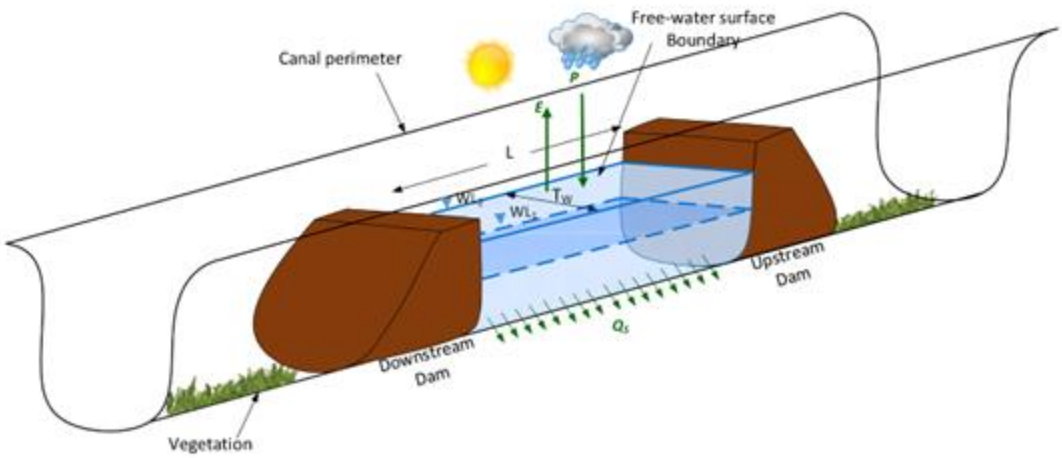


Figure 2-3 Illustration of the ponding method of measuring seepage along the reach of an irrigation canal (Lund et al., 2023)

The following formula is suggested for computing the rate of seepage (Kraatz, 1977).

$$S = \frac{W(d_1 - d_2)}{P} \quad [1.3]$$

Where S = average seepage in m^3/m^2/day; W = average width of water surface of the ponded reach (m); d_1 = depth of water at beginning of measurement (m) d_2= depth of water after 24 hours (m); and P = average wetted perimeter (m).

2.4.1.3. Seepage meter measurement

A seepage meter is a modified version of a constant head permeameter developed for use under water. Seepage meters are, in principle suitable for measuring local seepage rates in canals or ponds. They are particularly useful for locating sections of the canal with excessive seepage. As a precaution, installation of seepage meters should be done with least disturbance. Seepage meters should not be used in very gravelly soil due to difficulty of forcing the bell into the bed of the canal. Sandy soils are unsuitable for seepage meters use since there is danger of the seepage meter being washed away by the current (Nyagah, 1991).

Various studies have measured seepage loses in the field using different methods. Some of these studies are reviewed in this thesis, Skoperboe et al. (1999) studied a number of channels in the Fordwah Eastern Sadiqia Project using the inflow–outflow method. They considered, in the majority of cases, the inflow–outflow methods of measuring channel losses as highly preferred because the losses are being measured under the usual operating conditions. They suggested using the ponding method when channel losses are relatively low. They could not consider the ponding method a standard for evaluating channel losses, contrary to some other authors. However, some channels evaluated by them showed negative loss rate, which is unexplainable. Inflow-Outflow measurement method illustrates the losses that occur during conveyance of water in the open canals and are made without obstruction the operation of selected canal and additionally give measurements accurate enough (Akkuzu et al., 2007).

Lund et al. (2023) concluded that, the inflow-outflow method uses to determining the amount of seepage losses and consists of measuring the inflow to and outflow from the reach of the irrigation canal and calculating the difference between them, and this method adapts with the long canals have a few numbers of diversions, and also uses with small sections of the canal which has high seepage.

Sunjoto (2010) studied when using the inflow-outflow method, measurements are carried out over a short period, so evaporation losses can be neglected. The amount of evaporation from the open water surface is generally small, meaning that losses in the canal segment are primarily due to the seepage (Akkuzu, 2012). In general, evaporation losses in irrigation networks are usually not considered (Saeed & Khan, 2014).

The ponding method is used when the channel losses are relatively low. However, contrary to some authors, the ponding method cannot be considered a standard for evaluating channel losses. The reason is because it violates one major condition; instead of having a sloping water surface gradient representative of the channel under usual operating conditions, the ponding method creates a reservoir having a horizontal water surface. The only exception is in cases where the wind velocity results in one end of the pond having a higher water surface elevation than the other end of the pond. Also, it is well known that a pond filled with sediment-laden canal water will result in lower estimates of channel losses because these sediments are filtered as the "water seeps into the earthen embankment, thereby reducing the porosity of the soil at the wetted perimeter for a depth of only a few millimeters (mm), which is sufficient to significantly reduce the infiltration (seepage) into the bed and embankments (Skoperboe et al., 1999).

The point measurement method is conducted through the use of tracers or seepage meters to measure canal seepage by establishing a set of sample points. This method is often employed in small-scale canals and canal beds with a few weeds (Luo et al., 2005). The measuring device is simple and easy to operate. However, this method requires repeated reading and its results are heavily influenced by external factors. Hence, the method's measurement accuracy is limited.

In this study, the inflow-outflow test method is employed to measure field canal seepage losses. Since Laelay Wukro had shortage of water during the study period due to shortage of rainfall, so the irrigation time should not be interrupted.

2.4.2. Canal seepage loss estimation using empirical formulas

According to Hameed et al. (1996) an accurate estimation of conveyance water losses from an irrigation scheme is essential for the proper control of the system. Water managers are often under pressure to divert additional water to compensate for the losses and to ensure that users receive water according to their requirements. Therefore, for effective operational planning and management of an irrigation system, reliable forecasting of water losses is important.

Many scholars have conducted research and proposed various empirical formulas for different purposes. These include: Davison–Wilson, Moritz, Inghaln, Molesworth, Swamee and Muskat formulas (Hosseinzadeh Asl. et al., 2020; Barkhordari & Hashemy, 2022). Overall, those formulas are simple in form and can be applied conveniently. However, the values of the coefficients in the formulas vary widely, and their application involves numerous constraints; therefore, they are suitable only for specific situations. For example, complicated parameters and calculation processes are involved when the empirical formulas are used to deduce calculation formulas of canal seepage. Thus, the application of these formulas is limited. Some formulas developed for very specific, localized conditions, and others estimate more generalized situations (i.e. unlined or lined canals); others require canal discharge/velocity or the saturated permeability of the canal soils.

Description of some the most commonly used empirical formulas used in different studies is discussed below.

- **The Davis-Wilson formula**

Ashour et al. (2021) reported that the Davis–Wilson equation relates seepage loss directly to the cube root of the canal water depth, based on the assumption that infiltration occurs uniformly along the wetted perimeter. It is the only formula mentioned for estimating seepage in lined canals and includes recommended constant values for various soil types. In this approach, the square root of the average canal velocity is considered to have an inverse relationship with seepage loss, though its effect is deemed minimal.

$$q = 0.45C \frac{P_w * L}{4*10^6 + 3650\sqrt{V}} {H_w}^{1/3} \qquad [2.4]$$

The value of the coefficient C varies from 1 to 70 depending on the channel cover and is equal to 1.0 for concrete channels. The parameter Pw (m) is the wetted perimeter, L is length of the channel (m), V is the average velocity in the channel (m/s), H_W shows depth of water in the channel (m) and q is seepage from the channel along the channel length (m^3/s).

- **Moritz formula**

The Moritz formula (USBR, 1967; Kraatz, 1977) was proposed by the USBR for estimating seepage losses per kilometer of unlined canal is given as:

$$q = 0.0186C \left(\frac{Q}{V}\right)^{0.5} \qquad [2.5]$$

Where C is a constant the parameter q is the channel seepage rate over one kilometer (m^3/s), V is the velocity of the water in the channel (m/ s), and Q is the amount of discharge (m^3/s) in the channel.

Akkuzu (2012) analyzed both the Moritz and Davis–Wilson equations by comparing their seepage loss estimates with inflow–outflow test results on lined canals. The study revealed that both formulas underestimated the actual seepage losses, which was attributed to the deteriorated condition of the concrete linings. In the analysis, Akkuzu applied a metric adaptation of the Moritz equation, using a constant (C) value of 0.1 specifically for concrete-lined canals.

- **Moleswerth and Yennidumia formula**

The Molesworth-Yennidumia formula (Kraatz, 1977) used by the Egyptian Irrigation Department is given as:

$$q = 86.4C\sqrt{R} \qquad [2.6]$$

Here, q is the water seepage flux (m^3/sec), R is the hydraulic radius (m), and C is a coefficient different soil types.

Mowafy (2001) assessed multiple empirical and analytical equations by comparing their predictions with seepage test results from various sections of the Ismailia Canal in Egypt. The findings indicated that the Molesworth–Yennidumia empirical formula, along with the analytical models, closely matched the observed seepage data.

- **Swamee equation**

The Swamee equation was originally developed as a design tool for creating canals with minimal conveyance losses but has also been applied to estimate seepage. In this method, seepage is determined by multiplying the geometric factor **F**, the flow depth, and the permeability of the concrete lining. The geometric variable **F** is defined through a closed-form solution proposed by (Swamee et al., 2000). Its value does not vary much equation [2.7].

$$q = KyF \qquad [2.7]$$

Where: q: seepage discharge per unit length of canal (m^2/s) K: hydraulic conductivity of the porous medium (m/s) y: depth of water in the canal (m) F: function of canal geometry (dimensionless) (Swamee et al., 2000).

$$F = \left[\left(\left(\pi(4-\pi)\right)^{1.3} + (2m)^{1.3}\right)^{\frac{0.77+0.46m}{1.3+0.6m}} + (b/y)^{\frac{1+0.6m}{1.3+0.6m}}\right]^{1.3+0.6m/1+0.6m}$$

b: width of canal y: depth of flow m: side slope

- **Muskat formula**

The Muskat formula was derived by for canals with homogeneous, isotropic soils and deep water tables (Robinson & Rohwer, 1959):

$$q = \frac{K(B+2H)}{Wp} \qquad [2.8]$$

Where q is seepage rate (m ^{3} /m^2 /day); K is permeability (m/s); B is the width of water surface (m); H is the depth of water (m); and WP is the wetted perimeter (m).

The USBR evaluated Muskat's formula in conjunction with seepage loss tests performed on earth canals in Wyoming and Nebraska. They found it to be unreliable in predicting seepage rates due to the fact that the canal soils were primarily heterogeneous and anisotropic (Robinson & Rohwer, 1959).

- **Ingham equation**

$$q = 0.55 * 10^{-6} CPL\sqrt{H} \qquad [2.9]$$

Where q is the seepage (m^3/s), P is the wetted perimeter (m), L is the channel length (m), H is the depth of the water in the channel (m), and C is a coefficient that depends on the type of the soil. The value of the C varies between 1.5 and 5.5.

For this study the Davis–Wilson, Moritz, Molesworth & Yennidunia, Swamee, and Muskat empirical formulations. These were selected because they have been widely used for unlined canal seepage, cover a range from simple per-length loss estimates to semi-empirical hydraulic-conductivity based forms, require parameters available from field measurement or standard soil tests, and have been documented validation in irrigation schemes with alluvial and mixed textures (Arshad et al., 2020; Pavelic, 2021; Cedergren, 2021). Preliminary application to my study site data showed that these equations provide a useful spread of predicted losses for cross-validation with measured inflow–outflow.

2.4.3. Canal seepage estimation using numerical formula

Based on Darcy's law and a continuity equation, the two-dimensional partial differential Equation governs seepage through porous media.

Discharge in the soil follows the Darcy's law:

$$q = -KA\frac{\partial h}{\partial x} \qquad [2.10]$$

Where q is discharge seepage (m^3/s), K is permeability coefficient (m/s), A is the cross section of the water flow (m^2) and ∂h/∂x indicates the hydraulic gradient (m/m) of the flow.

The equation governing the flow of water in a porous medium is the Poisson equation, which is the generalized form of the Laplace equation.

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} = q \qquad [2.11]$$

Here, kx and ky are the hydraulic conductivity of the soil in the horizontal and vertical directions (m/s), respectively. The term h is the water potentiality in the soil (m), and q indicates the flow rate at the inlet or the outlet to the soil mass (m^3/s per unit soil volume). Equation [2.11] is applicable for the steady state flow. For unsteady flow, the equation is:

$$\frac{\partial h}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial h}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) = Q + \frac{\partial \theta}{\partial t} \qquad [2.12]$$

In which $\frac{\partial \theta}{\partial t}$ is the volumetric change in water content in time.

Solving the Poisson equation is mathematically complex; however, numerical methods provide an effective approach by transforming differential equations into algebraic ones. With the advancement and widespread use of computers, the application of numerical methods has become increasingly prevalent. These methods enable the solution of large systems of algebraic equations through iterative or matrix-based computational techniques (Rostamian & Abedi, 2011).

Solving the Poisson's equation is one of the most complex mathematical problems. The Seep/W software is one of the software used to solve the Poisson's equation using the finite element method (Salmasi et al., 2020). Due to the analytical solution difficulty of the above equation, a numerical solution based on a finite element approach was used to solve the governing equation using Seep/W (Krahn, 2004).

2.4.3.1. Numerical modeling using See/W

A numerical model represents a physical process through mathematical formulations. Seep/W is one example that accurately simulates water flow through porous or granular media. In contrast to laboratory-scale physical models or full-scale field experiments, numerical models depend entirely on mathematical computations, marking a key difference in how they replicate real-world behavior (Krahn, 2004).

The model Seep/W is a commercially available finite element method (FEM) package and it proves to be very efficient in carrying out seepage studies (Seep/W manual 2007). Seep/W has been officially used in many study areas of civil engineering , analysis of stability, and several more (Danoosh & Al-Hadidi, 2022). The Seep/W software is based on the finite elements method.

The finite elements numerical methods are based on the concept of dividing a structure into small pieces describing the behavior or function of these elements, and then connecting the elements to model the entire structure. This process is called meshing. Meshing is one of the three main aspects of the finite elements modeling and the two other ones are material properties and the definition of boundary conditions (Hosseinzadeh Asl. et al., 2020).

The numerical method is utilized to calculate canal seepage losses by simulating the actual situation in the site. The advantage of the numerical method is that canal seepage losses, as they change with time and space, can be obtained under various complicated conditions. However, most of the existing canal seepage models have certain limitations and need to be improved when used. The saturated–unsaturated flow model HYDRUS-2D has been applied to simulate canal seepage and local soil water response (Liqiang et al., 2012).

2.5. Evaluation criteria

In order to evaluate performance of different seepage estimation methods, predicted (estimated) results were compared with the field observations for the acceptability of the methods. Performance of any model is evaluated in the basis of statistical parameters that is mean error (ME), root mean square error (RMSE) and models efficiency (EF) (Arshad et al., 2018). If the comparison shows a good coincidence, the model developed can be recommended for practice. Salmasi et al., (2020) used the coefficient of determination (R^2), the relative error (RE) and the root mean square error (RMSE) statistical parameters to compare different methods of estimating seepage from the earthen channels. (Barkhordari & Shahdany, 2020) considered coefficient of residual mass (CRM) to evaluate simulated values with measured values of seepage. Elshaarawy & Elmasry (2024) evaluates simulated and observed results, the assessment based on correlation utilized several metrics, including the correlation coefficient (r), the index of agreement (d), and the Nash-Sutcliffe Efficiency (NSE). In contrast, the evaluation focused on errors incorporated measures such as root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and R-squared (R^2).

3. Materials and Methods

3.1. Description of the study area

The study area, Laelay Wukro irrigation scheme, is located in Tabia Mahbere hiwot, Tsirea woreda, and eastern zone of Tigray, Northern Ethiopia. The project is located at the right side of the main Wukro– Adigrat all-weather road near the town Wukro. Wukro is about 45 km to the north of Mekelle. The dam is located at about 2.2 km to the east of the Wukro Adigrat road. The command area extends from the dam up to the Wukro Adigrat road. Geographically the project site is located between 39°36´15´´ to 39°37´00´´ E and 13°48´10´´ to 13°49´10´´ N.

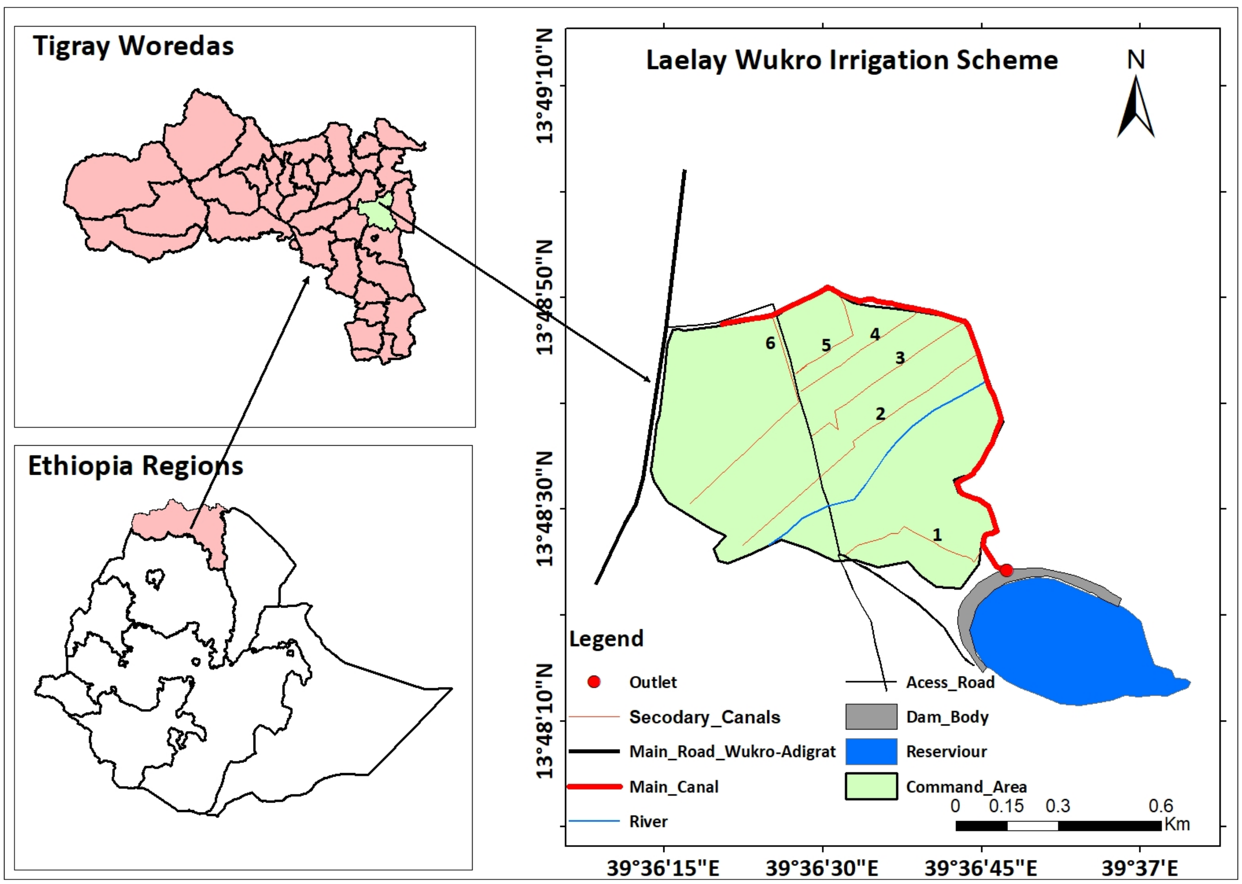


Figure 3-1 Location map of the study area

Laelay-Wukro small-scale irrigation project is one of the irrigation projects designed and constructed by Commission of Sustainable Agriculture and Environmental Rehabilitation in Tigray (Co-SAERT) in 1986/1987 E.C. The dam was designed and constructed to store 0.8473 Mm^3 of water from a catchment area of 9.16 km^2. To impound this amount of water a micro dam with dam height of 14.3m and crest length of 660m was designed and constructed to irrigate about 50 hectares of land. The mean annual rainfall of the study area is about 466mm. The maximum and minimum temperature ranges from 23 to 28°c and from 9 to 14°c, respectively. The area was classified as dry Weyna-Dega agro ecological zone and the topographic features of the area include mountain, cliff escarpments, hills and plain, with an elevation of 1500-2300 meters above mean sea level (Gutu, 2022).

3.2. Methods

The study was carried out during the irrigation season of 2024. Representative canals were selected based on clearly defined technical and logistical criteria to ensure reliable seepage evaluation. The selection considered accessibility, which enabled safe installation of measuring devices and repeated field observations. In addition, canal geometric characteristics, including shape, cross-sectional dimensions, and wetted perimeter, were considered due to their direct influence on seepage losses. Furthermore, hydraulic characteristics, particularly discharge capacity and flow stability, were used as selection criteria to ensure accurate inflow–outflow measurements. These criteria ensured that the selected canals were representative of the physical and hydraulic conditions of the irrigation scheme as shown Figure (3.2). Seepage losses were measured for a total of 6 unlined secondary canal segments. Losses due to evaporation were not considered with the assumption of its negligible proportion (Nyagah, 1991).

In choosing the canal to be measured and the placing of the segments, the following were taken into consideration i) the flow should be the normal operating condition of the canal, ii) there should be no change in water level during measurement, iii) there should be no water flow either from outside into the segment or from the segment to the outside, iv) there should be no disruption of the cross-sectional geometry of the segment where the measurement was taken and there should be nothing to prevent the flow, and v) the length of segment should be sufficient for measurement of conveyance loss (ANCID, 2003).

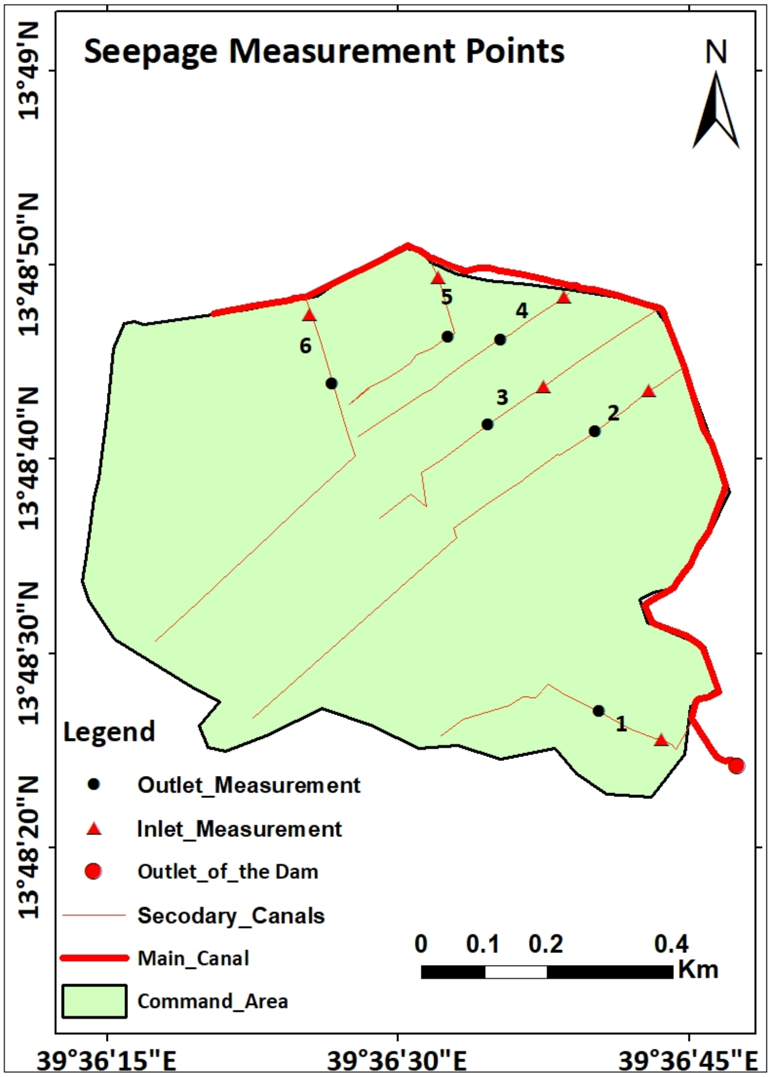


Figure 3-2 Selected canals and Seepage Measurement points Using Inflow-Outflow methods

3.2.1. Determination of hydraulic parameters of canals

The hydraulic parameters of the selected canals were determined through systematic field measurements and subsequent analytical calculations. Canal geometric characteristics, including bed width and top width, were measured at representative sections along each canal using a measuring tape. Flow depth was measured using a ranging rod at several points across the canal section, and the average depth was used for analysis.

Based on the measured geometric dimensions, the wetted perimeter and wetted cross-sectional area of the canals were calculated assuming a rectangular channel section. The wetted perimeter was determined as the sum of the bed width and twice the flow depth, while the cross-sectional flow area was calculated as the product of bed width and flow depth.

3.2.2. Canal bed soil texture measurements

Soil samples (one pit per segment) were collected along the canal's path from the bank of the canal at various depths to determine their characteristics (Singh & Sandilya, 2021). As (Barkhordari & Shahdany, 2020) indicated that, the maximum amount of pore-water pressure is at a distance of 3-4 times of the water depth in the canal, relative to the bottom of the canal and along the vertical profile of the soil. Therefore, soil samples were taken from the bank of the canals at depth ranges of 30cm to incorporate the variability of soil profile with depth. Since, the normal depth in the canal understudy is (0.23 cm); but the sampling depth is four times of the normal depth, and it is enough to incorporate the lateral flow condition in canal bottom and side (Liqiang et al., 2012). Two soil samples were taken in each layer to determine soil texture and measure hydraulic conductivity using a constant-head perimeter. The site of sample selected by transects walk and considering the reach at which inflow-outflow test could be done (Gutu, 2022). Hydrometer method analysis was carried out for all the soil samples, and percentage of sand, silt, and clay was determined. The textural classifications were carried out for the types of soil using the triangular classification.

3.2.3. Measurement of canal discharge

The flow discharge across the unlined secondary canals were measured for estimating seepage losses of unlined secondary canals of Laelay-Wukro irrigation scheme using empirical methods. The area-velocity method as shown in equation [3.4], was used for the measurement of canal discharge. The velocity–area method of discharge measurement was applied by dividing the channel cross-section into five vertical subsections**,** depending on channel width, and measuring flow depth and velocity at each vertical. The flow discharge across the unlined secondary canals were measured, and using a tape meter the canal's wetted width and depth were measured along the length of canal segments at five selected measured points for each unlined secondary canals.

a) Wetted cross-sectional area

In this method, flow cross-section was divided into some vertical sections according to channel geometry. The wetted cross-sectional area was determined well-chosen segments of the canal using equation [3.1]. Data on the average wetted width and average wetted depth are used to estimate the average wetted cross-sectional area. During each measurement, the water surface width of the canal was divided into vertical subsections at 20–30 cm intervals**,** selected in accordance with standard velocity–area measurement practice for small irrigation canals, to ensure adequate representation of lateral variations in flow depth and velocity. At the same time water depths of each section were measured and cross- sectional areas of each partition were determined.

$$A_w = b * y \qquad [3.1]$$

Where, A_w: area of wetted cross sectional canal (m), b: bottom width of the canal (m), y: wetted depth of the canal (m)

b) Velocity measurement

In this study, the floating (surface float) method was used to determine the flow velocity at selected stations. This method is widely applied in small open channels and irrigation canals due to its simplicity and practicality under field conditions. Although the floating method measures surface velocity rather than depth-averaged velocity, reliable estimates of mean flow velocity can be obtained by applying an appropriate correction coefficient, typically ranging from 0.80 to 0.9 (Nancy et al., 1992). Several studies have reported that, when properly applied, the floating method provides acceptable accuracy for discharge and hydraulic assessments in small canals (Huda & Rather, 2023).

The float method is best suited for obtaining rough estimates of discharge and is particularly useful when conventional flow-measuring instruments are unavailable, when flow velocity is very low or water depth is too shallow for accurate current-meter readings, when floating ice or other obstructions prevent the use of a current meter, or when only an approximate discharge estimate is needed. Recent studies continue to support the use of surface float techniques as a practical approach for discharge estimation in small streams and open channels, particularly where resource or access constraints limit the use of more advanced instrumentation (Stepenuck et al., 2024).

Procedure: Two taglines (measuring tapes) were strung at right angles to the flow across the channel at locations marking the beginning and end of the measurement section. The lines are far enough apart, typically at least two to three channel widths, to allow a travel time for the float of at least 20 seconds. Surface float consisting of a seed of smaller size (diameter in cm) floats and specific gravity close to unity was floated through the channel (Abed, 2021). A single velocity measurement starts with throwing a float into the channel at a location far enough upstream of the upstream line so that the float is moving in the direction and at the speed of the water when it passes that line. The time taken for the float to pass between the upstream and downstream lines was recorded. The process were repeated five times depending upon the size of the channel at several subsections at varying distances from the bank by aiming the toss of the float at the center of each subsection.

Therefore, float velocity is calculated as the distance (L) between lines divided by the average travel time (seconds) of the floats between the lines.

$$V_s = \frac{L}{t} \qquad [3.2]$$

Based on California Water Boards Float Method guidance, the float method quantifies only surface velocity; in reality the surface velocity is usually greater than the average velocity of the full vertical depth of flow. Therefore, the average flow velocity was determined by multiplying the average float velocity by an adjustment coefficient. Selection of the value of the adjustment coefficient can be imprecise because its value is a function of the roughness of the channel bed. It’s usually possible only to know bed roughness at a coarse level. Lower values (e.g., 0.8) are given for rough beds versus higher values (e.g., 0.9) for smoother, sand/silt beds (Nancy et al., 1992), typically used for this study was 0.9. Since the bed material from laboratory ranging from loamy sand to clay loam which is smoother category.

$$V_a = 0.9 * V_s \quad [3.3]$$

Where, V_a: average velocity, V_s: surface velocity

Table 3-1 Flow velocity of unlined secondary canal

Canal section name	surface velocity (V_s) in m/s	average velocity (V_a) in m/s ($0.9 * V_s$)
Sc1	0.391	0.352
Sc2	0.263	0.236
Sc3	0.306	0.276
Sc4	0.447	0.402
Sc5	0.523	0.471
Sc6	0.492	0.446

After estimating the average velocity and the wetted cross-sectional area, total discharge was calculated by multiplying the combined area of all cells by the average velocity calculated from float trials, and by the adjustment factor (0.9) which is continuity as given in equation [3.4].

$$Q = A_w * V_a \quad [3.4]$$

Where, Q: Discharge of canal, A_w: wetted cross- sectional area, V_a: average velocity

3.2.4. Measurement of seepage losses by direct field method

Conveyance water losses measurements were made by inflow-outflow because the inflow-outflow method is considered one of the practical and reasonably accurate methods under dynamic flow conditions suited to actual field conditions (Agri et al., 2015). The method involves measurement of discharge at two points. The initial point was considered as inflow and the other point at a downstream side as outflow and efforts were made to observe all the visible possible causes which could contribute to the losses from the watercourses. On each watercourse two flumes of 8" × 1.5' size were installed at 100m length difference (Zeb et al. 2000). The flumes were checked using a carpenter level both in longitudinal and transverse section. After checking the level of the flumes, they were completely sealed from sides and bottom with the mud. The level of the flumes, was again checked after sealing. The time of installation was noted on wrist watch. Before taking any reading on flume, it was ensured that the flow of water was steady through the flume and without any obstruction or trashes in order to avoid hindrance in flow. After 30 minutes, the flow was closely observed for uniformity and steadiness.

The following formula was used to calculate water conveyance loss in defined canal sections of sufficient length.

$$Q_s = \frac{Q_i - Q_o}{L} \qquad [3.5]$$

Where: Q_s = seepage losses (m^3/s); Q_i = inflow discharge at inlet/start- point of selected reach length of the canal (m); Q_o = outflow discharge at endpoint of reach (m^3/s).

However, evaporation losses in this study have not been considered since different literatures states that the evaporation losses in irrigation networks is generally not taken into consideration (Xie et al., 1993; Kanber 1997; ANCID 2000).

Seepage loss in the canals was calculated in two different ways: i) conveyance loss per unit of canal length ($l\ s^{-1}\ 100\ m^{-1}$), ii) conveyance loss as a percentage of inflow and (% per 100 m), (LWRRDC, 2002).

3.2.5. Seepage estimation by empirical formulae

Various studies in literature have used and discussed empirical equations to quantify seepage from irrigation canal networks (Mowafy, 2001; Akkuzu, 2012; Han et al., 2021). These equations are simple and easy to use in comparison with other measurement methods. These equations are based on the hydraulic profile of canals, such as discharge, velocity, channel geometry, and soil characteristics.

When the canal bed is composed of different soil layers the seepage path doesn’t have a single uniform conductivity. So, using one constant “C” value may cause significant error. In this case, an equivalent seepage coefficient (C_{eq}) was used for the composite soil profile. The equivalent coefficient can be computed using the concept of flow through layered media (Darcy’s law).

$$C_{eq}\ or\ K_{eq} = \frac{T_{total}}{\sum_{i=1}^{n} Ti/Ci} \qquad [3.6]$$

Where: $T_{total:}$ - total thickness of all layers below canal bed, Ci = empirical seepage or permeability coefficient for each layer, Ti = thickness of each layer.

Since the canal bed is composed of different soil layers in this study from laboratory test, C-values were selected according to the soil texture and measured hydraulic conductivity of each canal section. Coarser soils with higher hydraulic conductivity (sandy loam) were assigned larger C-values, while finer soils (clay loam) with lower conductivity were given smaller C-values (Hosseinzadeh Asl. et al., 2020); Ashour et al., 2023).

Table 3-2 the value of the constant coefficient C_{eq} and K_{eq} in the empirical equations

	C_{eq} values of empirical equations				K_{eq} values (m^3/sec)	
canal sections	Davis–Wilson	Moritz	Molesworth and Yennidunia	Ingham	Swamee	Muskat
SC1	25	0.66	0.003	3.35	8.286E-06	8.286E-06
SC2	23	0.61	0.0028	3.62	7.566E-06	7.566E-06
SC3	25	0.66	0.003	3.35	1.600E-06	1.600E-06
SC4	17.3	0.47	0.0024	4.09	1.494E-06	1.494E-06
SC5	16.36	0.45	0.0024	4.18	1.411E-06	1.411E-06
SC6	21.4	0.66	0.003	3.35	1.671E-06	1.671E-06

Seepage losses in the studied six unlined secondary canals were estimated using 6 empirical equations as presented in Table3.4.

Table 3-3 Empirical equations studied in this research

Serial No	Empirical Formula	Equation	Description
1	Davis–Wilson (Akkuzu, 2012)	$q = 0.45C\frac{P_w * L}{4 * 10^6 + 3650\sqrt{V}}H_w^{\frac{1}{3}}$ [3.7]	q = seepage losses ($m^3 \cdot s^{-1}$); L = length of canal (m); P_w = wetted perimeter (m); Hw = flow depth (m); v = flow velocity ($m \cdot s^{-1}$); C = coefficient
2	Moritz (Shah et al., 2020)	$q = 0.0186C\left(\frac{Q}{V}\right)^{0.5}$ [3.8]	S = seepage losses ($m^3 \cdot s^{-1}$ per km length of canal); Q = inflow canal ($m^3 \cdot s^{-1}$); v = flow velocity ($m \cdot s^{-1}$); C = coefficient
3	Molesworth and Yennidunia (Egyptian)(Mowafy, 2001)	$q = C * L * Pw * \sqrt{R}$ [3.9]	S = seepage losses ($m^3 \cdot s^{-1}$); L; length in Km, Pw; wetted perimeter (m), R = hydraulic radius (m); C = coefficient
4	Swamee (Swamee, et. al. 2000)	$q = KyF$ [3.10]	q: seepage discharge per unit length of canal (m^3/s) K: hydraulic conductivity of the porous medium (m/s) y: depth of water in the canal (m) F: function of canal geometry (dimensionless)
5	Muskat (Robinson & Rohwer, 1959)	$q = \frac{K(B + 2H)}{Wp}$ [3.11]	q; is seepage rate (m^3/m^2 /day); K is permeability (m/day); B is the width of water surface (m); H is the depth of water (m); and W_P is the wetted perimeter (m).
6	Ingham(Salmasi & Abraham, 2020)	$q = 0.55 * 10^{-6}CPL\sqrt{H}$ [3.12]	q; is the seepage (m^3/s), P is the wetted perimeter (m), L is the channel length (m), H is the depth of the water in the channel (m), and C is a coefficient

3.2.6. Seepage estimation by numerical formulae

In recent years, with the rapid development of finite-element technology, the application of the finite-element method in seepage calculation has increased (Zhang et al., 2017). To develop a numerical model of Laelay Wukro Canal by using Seep/W software, in first try one cross sections from each of six reaches with average bed width and flow depth were selected. After the selection of cross sections, the Seep/W software were used to generate FEM mesh and the seepage analysis was carried out accordingly. After the mesh formation, the material properties obtained from Laboratory are then assigned. Once the model fully developed, the boundary conditions are then assigned as Dirichlet (Head at canal water surface) and Neumann (flux specified) boundary nodes (Arshad et al., 2018). After the development of complete model, it was then verified by the Seep/W software and computation for seepage was carried out accordingly. Finally estimated results obtained from the Seep/W software for each section are compared with the field measured data.

In this research work, finite element approach was employed to solve the governing differential equation pertaining to seepage through unearthed canal. The Seep/W software (program) is a sub-program of the Geo Slope (software) computer, which is used to cater for seepage problems through porous soil media. Seep/W is a FEM based CAD type software used to analyze seepage and groundwater flow problems (Geo-Slope, 2012).

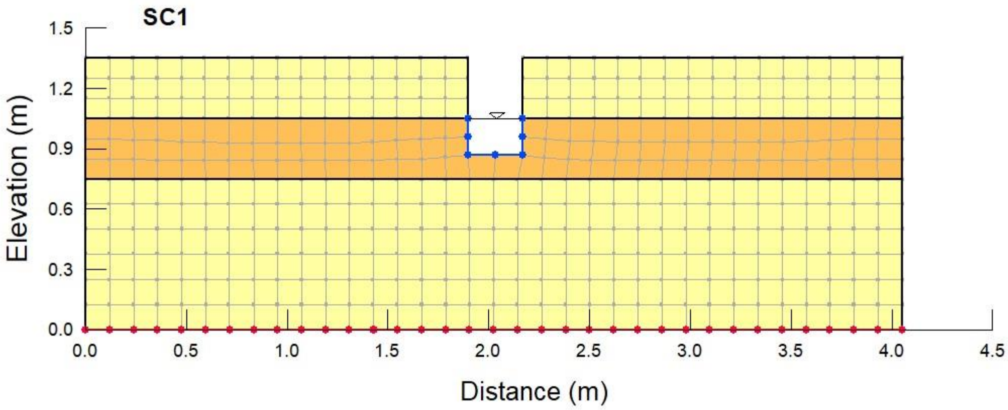
The equation governing the flow of water in a porous medium is the Poisson equation, which is the generalized form of the Laplace equation.

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} = q \qquad [3.13]$$

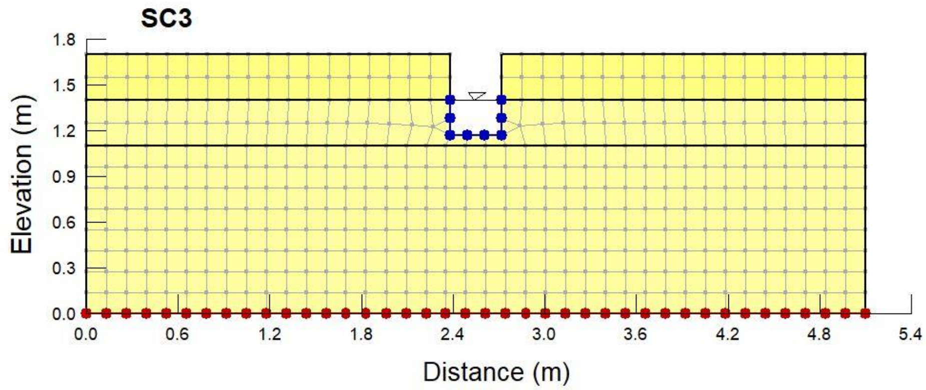
Here, kx and ky are the hydraulic conductivity of the soil in the horizontal and vertical directions (m/s), respectively. The term h is the water potentiality in the soil (m), and q indicates the flow rate at the inlet or the outlet to the soil mass (m^3/s per unit area). Solving the Poisson's equation is one of the most complex mathematical problems. The Seep/W software solves the Poisson's equation employing the finite element method.

FEM mesh formation and its verification by using Seep/W software

To create a two-dimensional finite element model, the Seep/W model of Geo-Slope software (GeoStudio 2018 R2, version 9.1.1.16749) was utilized to analyze seepage losses. Initially, a finite element mesh was developed using the steady-state seepage approach in Seep/W (Akkuzu, Baber, & Irfan, 2018). The mesh elements are composed of two types i.e. square and rectangles appropriate mesh of 0.2 meters (Salmasi et al., 2020). The domain is discretized in to mesh by 926 elements and 852 nods for cross section canal three and 450 elements 398 nodes for the other five canal cross sections as shown Figure 3.4 (a) and (b).



(a)



(b)

Figure 3-3. (a), (b) Mesh formation for Laelay-Wukro secondary irrigation canals

The boundary conditions

In numerical studies of the irrigation channels for seepage problems, a lateral distance from the right and left sides of the channel cross section and significant depth below the channel bed should be considered. As Salmasi et al. (2020); ANCID (2003) recommended, the distance between the lateral boundaries in the rectangular channels is 15 times the width of the water channel surface and the significant depth below the channel bed, affecting the seepage rate is considered to be approximately five times the bed width of the channel. In order to solve the model numerically, boundary conditions are first created and then assigned to the mesh. In all the cases Neumann type boundary conditions with zero flux condition is executed on the bottom of the mesh. Furthermore, Dirichlet, boundary conditions (FSL level) are assigned to the channel cross section respectively (Barkhordari & Hashemy 2022).

Once the material properties and boundary conditions were defined, the flux section was implemented within the mesh to calculate the seepage flux. This flux section was positioned at the midpoint of the cross-section for all scenarios. After entering all required parameters, the Seep/W software validated the mesh structure, confirming that both vertical and horizontal meshing were adequately stable and free from errors. Consequently, the model was deemed ready for computation and subsequent result analysis (Akkuzu et al., 2018).

Flow lines, velocity vectors and seepage flux

The seepage analyses for Sections SC1, SC2, SC3, SC4, SC5 and SC6 using the Seep/W module of GEO-SLOPE reveal consistent and realistic seepage patterns through the earthen canal bed and foundation. In all sections, the equipotential lines and flow vectors intersect nearly at right angles, confirming compliance with seepage theory and indicating accurate model performance. The total head distribution shows a gradual decrease from the canal water surface toward the lower boundaries, reflecting the steady dissipation of hydraulic energy. Higher seepage velocities and steeper hydraulic gradients are observed near the canal bed and side slopes, with flow gradually dispersing and slowing with depth. Among the six sections, minor variations in head distribution and flow vector density suggest differences in local permeability and soil layering, with SC3 showing slightly higher gradient concentration near the bed and SC5 displaying relatively more uniform flow dispersion. Overall, the seepage patterns indicate stable hydraulic behavior across all sections without signs of concentrated flow or potential piping, signifying effective seepage control and consistent soil response under steady-state conditions. The trend of the equipotential lines and flow lines (velocity vectors) are almost same in all cross sections as shown in Figure (3-5, 3-6, 3-7, 3-8, 3-9 and 3-10). The figure presents the seepage flow pattern through the canal section generated using the Seep/W module of GEO-SLOPE. The colored contours represent the distribution of total head, while the black lines depict equipotential lines, and the dashed arrows indicate the seepage velocity vectors (flow lines).

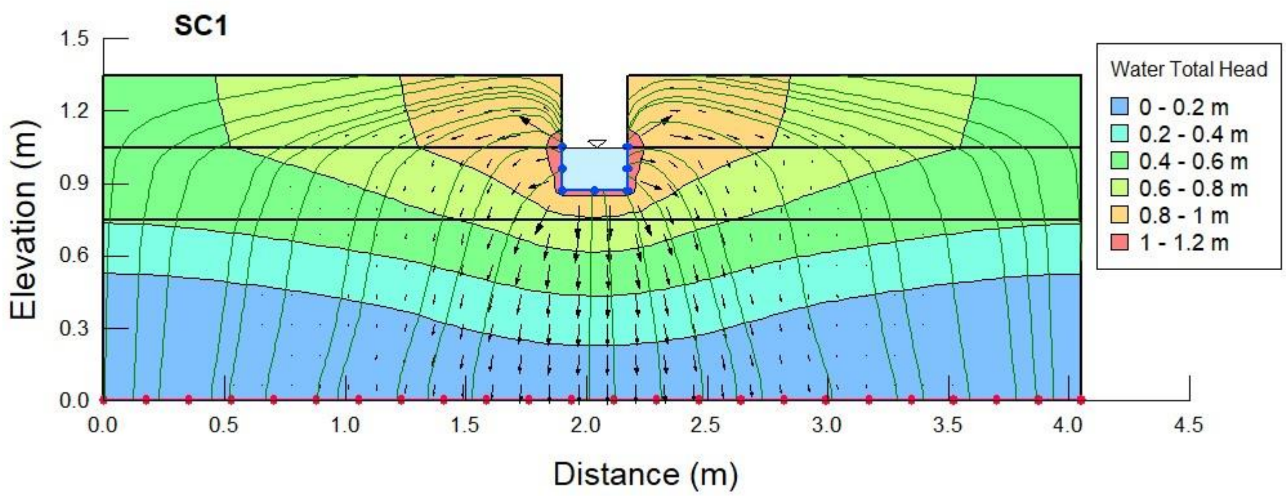


Figure 3-4 Flow-net Laelay Wukro canal for SC1 (Seepage = 1.233E-05 $m^3/sec/m^2$)

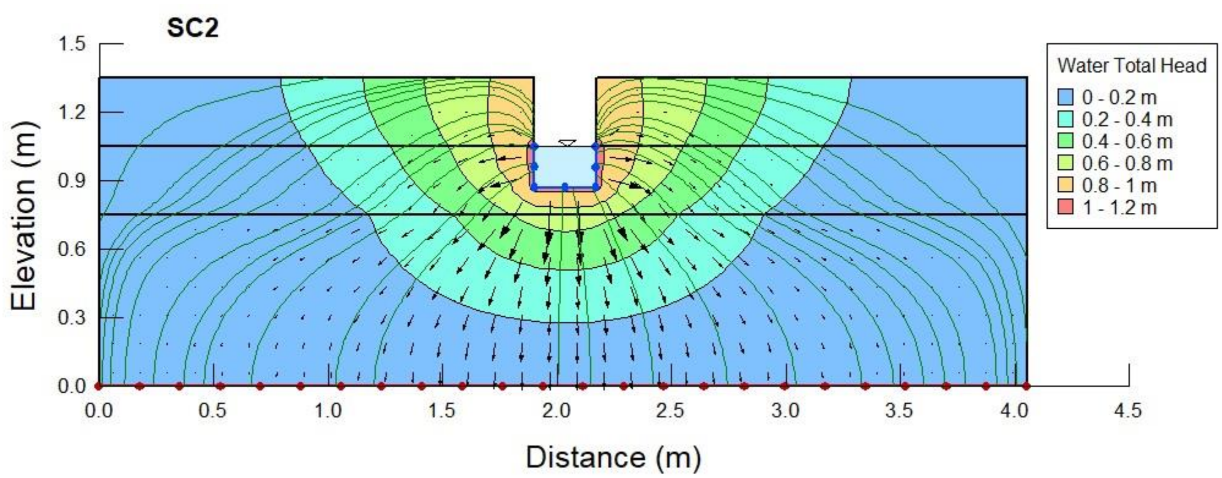


Figure 3-5 Flow-net Laelay Wukro canal for SC2 (Seepage = 1.872E-05 $m^3/sec/m^2$)

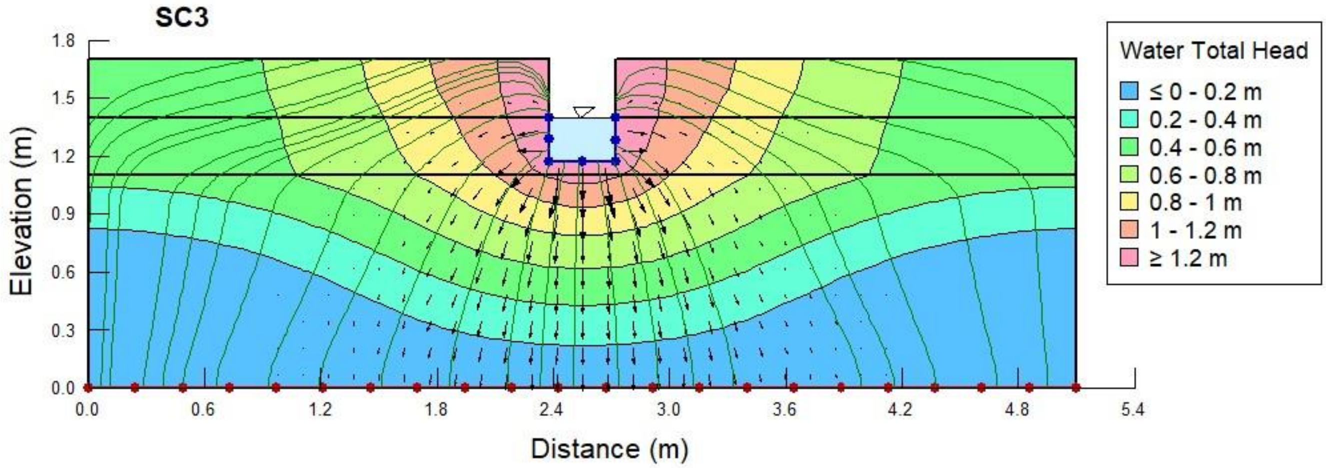


Figure 3-6 Flow-net Laelay Wukro canal for SC3 (Seepage = 4.499E-05 $m^3/sec/m^2$)

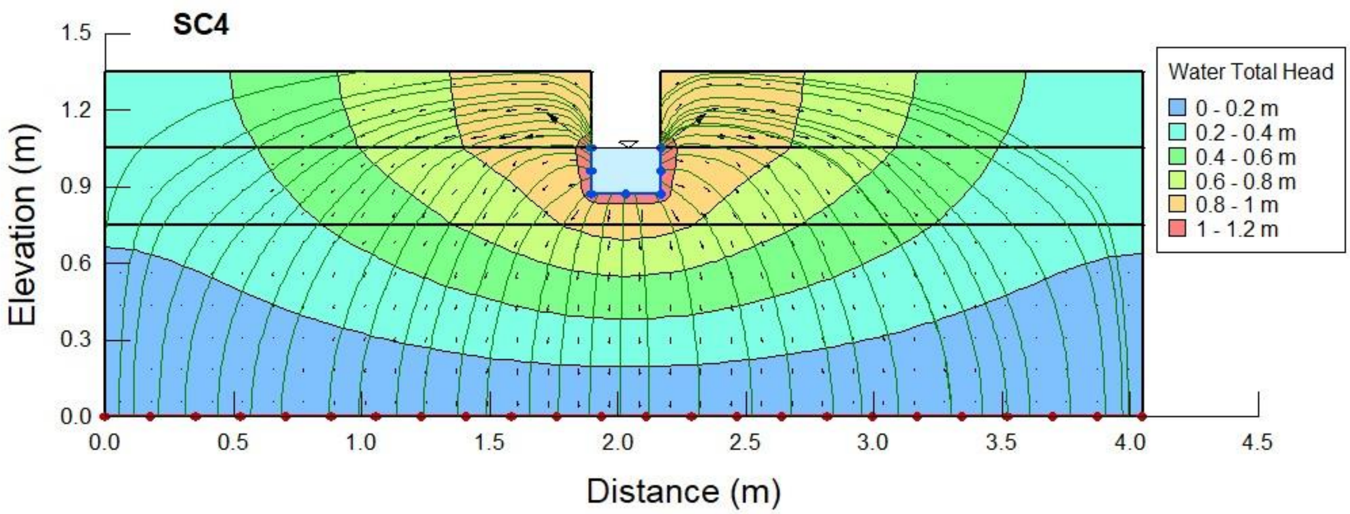


Figure 3-7 Flow-net Laelay Wukro canal for SC4 (Seepage = 5.706E-06 $m^3/sec/m^2$)

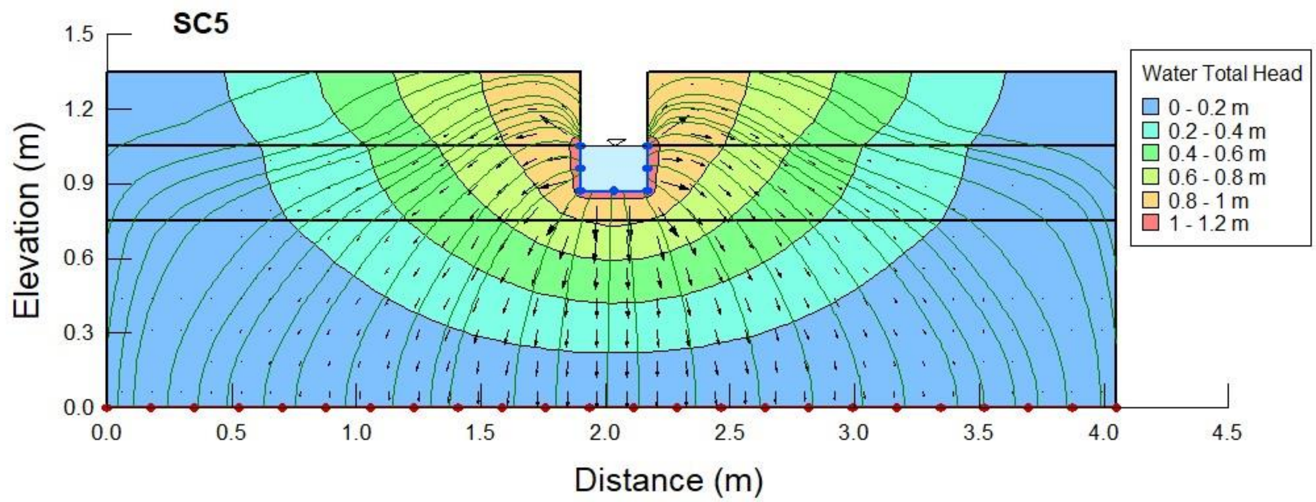


Figure 3-8 Flow-net Laelay Wukro canal for SC5 (Seepage = 2.258E-06 $m^3/sec/m^2$)

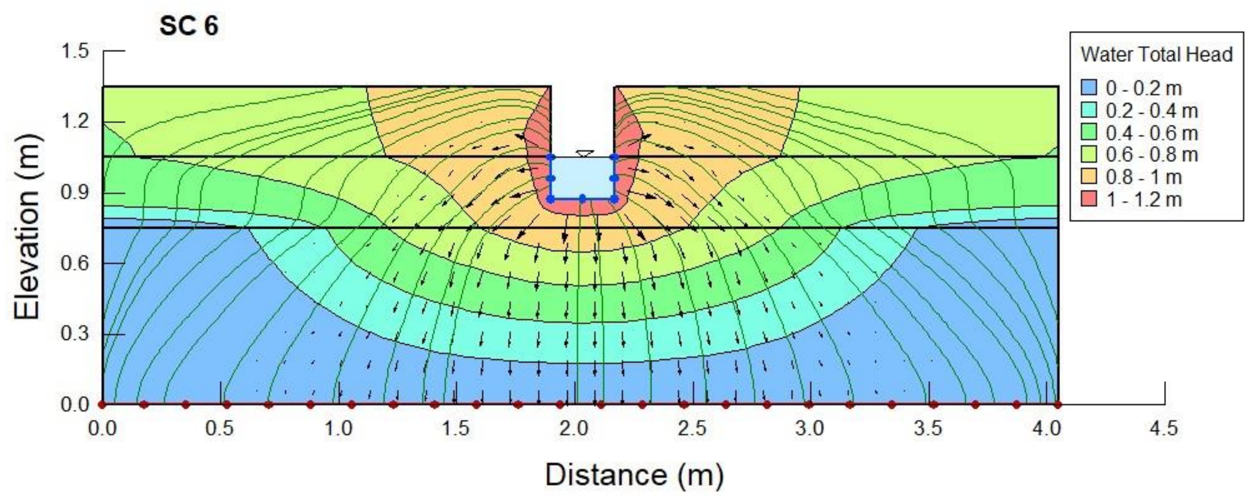


Figure 3-9 Flow-net Laelay Wukro canal for SC6 (Seepage = 2.109E-05 $m^3/sec/m^2$)

3.2.7. Comparative analysis of field measured and estimation methods

According to the below Equations, the statistical analysis of the coefficient of determination (R^2) and the root mean square error (RMSE), model efficiency (EF), coefficient of residual mass (CRM) were used to compare between estimated and experimental methods for estimating the seepage rates (Akkuzu et al., 2018).

1. Coefficient of determination (R^2)

The coefficient of determination is also used to determine the success of the model. R^2 is unit less and describes the portion of the total variance in the observed data as can be explained by the equation. The range is from 0 (poor estimates) to 1.0 (better estimates). The Value of R^2 was determined using Equation

$$R^2 = \frac{\left(\sum_{i=1}^{N}(P_i-\bar{P})*(O_i-\bar{O})\right)^2}{\sum_{i=1}^{N}(P_i-\bar{P})^2*(O_i-\bar{O})^2} \qquad [3.14]$$

2. Root mean square error (RMSE)

The RMSE provides a measure of the deviation of predicted values from measured data and has frequently been used as a means of evaluating the accuracy of hydrologic models (Turner, 2006). It is the most commonly used method to measure the success of the model. The Root Mean-Squared Error is the square root of Mean-Squared-Error after it is given the same dimensions as the estimated values themselves

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(P_i-O_i)^2)}{N}} \qquad [3.15]$$

Where, the Pi and Oi are simulated and measured variables, respectively, and $\bar{P_i}$& $\bar{O_i}$ are the mean values of the simulated and the measured, and n is the total number of data. The lower the RMSE indicator and the higher the R^2 value the more accurate the method will be.

3. Maximum absolute error (MAE)

The maximum absolute error is used to measure success of numeric estimation

$$MAE = max(\left|P-O\right|) \qquad [3.16]$$

4. Coefficient of Residual Mass (CRM)

The Coefficient of Residual Mass (CRM) is a statistical performance indicator used to evaluate how well a model or method.

$$CRM = \frac{\sum_{i=1}^{N}(O_i-P_i)}{\sum_{i=1}^{N}O_i} \qquad [3.17]$$

Where, the Pi and Oi are simulated and measured variables, respectively, and $\bar{P_i}$& $\bar{O_i}$ are the mean values of the simulated and the measured and N is the total number of data.

5. Percentage of Average Error (PAE)

$$PAE = \frac{\sum_{i=1}^{N}\left(\frac{P_i - O_i}{O_i} * 100\right)}{N} \quad [3.18]$$

6. Bias

Bias measures the average tendency of predictions or estimates to be higher or lower than the actual values. It can expressed as:-

$$Bias = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N} \quad [3.19]$$

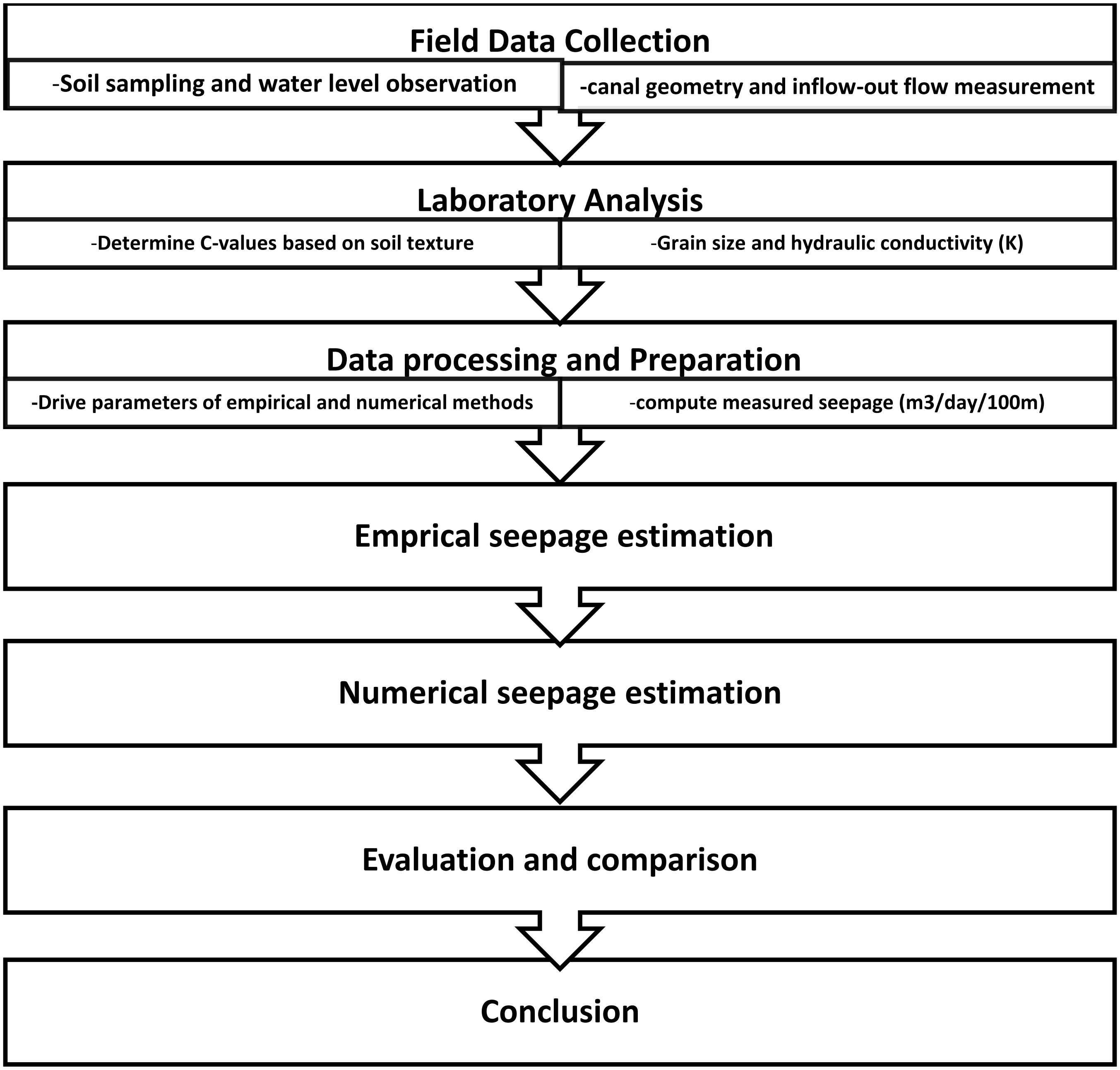


Figure 3-10. Overall methodological framework for data collection, processing and evaluation of seepage estimation

4. Results and Discussion

4.1. Soil texture of selected unlined secondary canals under study

The estimated values of different soil fractions of clay, silt, and sand at different depths and selected locations are given in Table 4.1. It was observed that the percentage of clay, silt and sand fractions varied from 4 to 35%, 1 to 36%, and 35 to 89% respectively. The average percentage values of sand are higher than the percentage of silt and clay. The soil textures of the selected secondary channels were sandy loam, sandy clay loam, loam, loamy sand and clay loam. These soils have coarser particles, and thereby the canal lines have high permeability. Due to the variation of coarser particles in the collected soil samples, the hydraulic conductivity varies from 0.3 cm/hr to 10.72 cm/hr. The highest value of hydraulic conductivity was 10.72 cm/hr at canal section 1(SC1) and the lowest was 0.3 cm/hr at canal section 6 (SC6).

Table 4-1 Soil profile division into distinct zones based on soil texture, and related soil hydraulic conductivities for each canal section.

Canal section name	**sample code**	**soil depth(cm)**	**%sand**	**%silt**	**%clay**	**Textural class**	**hydraulic conductivity(m/s)**
	S1d1	0 - 30	81	15	4	Sandy Loam	2.978×10^{-5}
SC 1	S1d2	30 - 60	65	14	21	Sandy clay loam	5.0×10^{-6}
	S1d3	60 - 90	68	15	17	Sandy loam	7.76×10^{-6}
	S2d1	0 - 30	54	30	16	Sandy Loam	7.1389×10^{-6}
SC 2	S2d2	30 - 60	49	34	17	Loam	6.139×10^{-6}
	S2d3	60 - 90	71	15	14	Sandy Loam	1.072×10^{-5}
	S3d1	0 - 30	77	9	14	Sandy Loam	1.158×10^{-5}
SC 3	S3d2	30 - 60	89	1	10	Loamy Sand	1.925×10^{-5}
	S3d3	60 - 90	85	6	9	Loamy Sand	2.033×10^{-5}
	S4d1	0 - 30	79	7	14	Sandy Loam	1.186×10^{-5}
SC 4	S4d2	30 - 60	39	27	34	Clay loam	1.278×10^{-6}
	S4d3	60 - 90	35	28	37	Clay loam	9.167×10^{-7}
	S5d1	0 - 30	39	36	25	Loam	2.972×10^{-6}

SC 5	S5d2	30 - 60	35	30	35	Clay loam	1.139×10^{-6}
	S5d3	60 - 90	41	25	34	Clay loam	1.139×10^{-6}
	S6d1	0 - 30	59	23	18	Sandy Loam	6.361×10^{-6}
SC 6	S6d2	30 - 60	53	19	28	Sandy clay loam	2.194×10^{-6}
	S6d3	60 - 90	51	14	35	Sandy clay loam	8.333×10^{-7}

SC1= Secondary canal 1 …SC6 = secondary canal 6, S1d1 =sample one depth one, S1d2 = sample one depth two, S1d3 sample one depth three …….S6d1= sample six depth one, S6d2= sample six depth two, S6d3= sample six depth three

4.2. Measurement of hydraulic parameters of selected watercourses

The hydraulic parameters for the six canal sections (SC1–SC6) are summarized in Table 4.2. This data contains about the dimensions of canals, length experiment of each secondary canals (SC), design discharge and velocity of each canal. Some of these data were collected from CO-SAERT and checked along field measurement. Other data such as length of canal were collected using tape meter measurements and GPS measurements and hydraulic parameters. The average bed width of the canals range from 0.27 m to 0.34 m, while the mean flow depth varies between 0.18 m and 0.23 m**.** These values indicate that the system consists of small-scale field canals, typically used for secondary water distribution in irrigation networks. The average velocity of flow across the canal sections ranges from 0.236 m/s (SC2) to 0.471 m/s (SC5), while the discharge ranges from 0.01 to 0.02 m^3/s. These values confirm that the system conveys water under stable subcritical flow conditions, typical of small earthen canals (Subramanya, 2008).

The measured velocities are within the safe range for earthen canals (generally below 0.5 m/s)**,** indicating that the system is hydraulically stable and not prone to erosion under current flow conditions(FAO, 2012).

Table 4-2 Hydraulic parameters of selected watercourses.

canal section name	average bed width (m)	average flow depth(m)	cross sectional area(m^2)	average velocity(m/s)	wetted perimeter(m)	hydraulic radius (m)	canal discharge (m^3/sec)
SC 1	0.27	0.18	0.049	0.352	0.63	0.077	0.02

SC 2	0.27	0.18	0.049	0.236	0.63	0.077	0.01
SC 3	0.34	0.23	0.078	0.276	0.8	0.098	0.02
SC 4	0.27	0.18	0.049	0.402	0.63	0.077	0.02
SC 5	0.27	0.18	0.049	0.471	0.63	0.077	0.02
SC 6	0.27	0.18	0.049	0.446	0.63	0.077	0.02

(Source: CO-SAERT, 2016 GC irrigation infrastructure design report on Laelay-Wukro irrigation project and my own study)

4.3. Seepage losses by inflow-outflow method

The seepage losses along different sections of the canal (SC1–SC6) were determined using inflow–outflow measurements for 100 m lengths of each section. The observed seepage losses ranged between 0.22 L/s and 0.93 L/s, corresponding to 2.8 % to 11.8 % of the inflow. These variations highlight the spatial heterogeneity of the canal bed and sidewall conditions, which directly influence the infiltration capacity of each section.

Among the studied sections, SC3 recorded the highest seepage loss (0.93 L/s or 11.8 %), due to coarse-textured soils (sandy loam), bed material and its cross- section variation. In contrast, SC5 exhibited the lowest loss (0.22 L/s or 2.8 %), indicating relatively better water retention, likely due to finer soil texture (clay loam). The moderate losses observed in other sections (SC1, SC2, SC4, and SC6) fall within a typical range for unlined earthen canals reported in literature.

According to studies by Bhuiyan et al. (1997) and Mishra & Sharma (2001), seepage losses in unlined distributaries and minors can vary from 3 % to 15 % of the inflow, depending on soil type, canal geometry, and maintenance condition. The observed losses in this study (2.8 %–11.8 %) are therefore consistent with these established ranges. Similarly, (FAO, 2010) reported that earthen irrigation canals generally experience seepage losses of 20–50 m^3/day per 100 m of length under typical field conditions. The results here (19–80 m^3/day per 100 m) align closely with those benchmarks.

Overall, the seepage loss assessment demonstrates that the canal network under study performs within acceptable limits for unlined earthen systems. However, localized problem areas (notably SC3) could benefit from remedial measures to improve overall conveyance efficiency and reduce water wastage.

Table 4-3 Seepage losses determined by direct field method (Inflow-Outflow)

canal section	Inflow(l/s)	Outflow(l/s)	seepage loss per 100m of watercourse			
			l/s	m3/s	m3/day	% of loss
SC 1	7	6.59	0.41	4.1E-04	35.424	5.8
SC 2	7	6.6	0.4	4.0E-04	34.56	5.7
SC 3	7.87	6.94	0.93	9.3E-04	80.352	11.8
SC 4	8	7.72	0.28	2.8E-04	24.192	3.5
SC 5	7.75	7.53	0.22	2.2E-04	19.008	2.8
SC 6	9	8.36	0.64	6.4E-04	55.296	7.1

4.4. Seepage loss estimated by empirical and numerical methods and its comparison

4.4.1. Estimated seepage losses by empirical and numerical methods

Seepage losses were estimated for six canal sections (SC1–SC6) using six empirical methods Davis–Wilson, Moritz, Molesworth and Yennidunia, Swamee, Ingham, and Muskat—and the numerical (SEEP/W) approach. These results were compared against measured inflow–outflow seepage values to evaluate the reliability and accuracy of each method. The estimated values are presented in Table 4.4.

Table 4-4 Estimated results for selected cross section(s) of Laelay Wukro unlined secondary canal

canal section	Seepage loss estimation methods (m^3/day/) per 100 m length							Measured
	Davis–Wilson	Moritz	Molesworth and Yennidunia	Swamee	Ingham	Muskat	Numerical (Seep/w)	(Inflow-Outflow) (m^3/day)
SC1	8.63	23.38	4.53	15.31	4.25	71.59	28.752	35.424
SC2	7.94	21.61	4.22	13.98	4.59	65.37	43.679	34.56
SC3	11.90	29.66	6.49	3.78	6.10	13.824	104.969	80.352
SC4	5.97	16.65	3.62	2.76	5.19	12.90	13.311	24.192
SC5	5.65	15.94	3.62	2.6071	5.30	12.19	5.266	19.008
SC6	7.39	23.38	4.53	3.08	4.25	14.43	49.20	60.48

Measured seepage values varied widely (from 5.27 to 104.97 m^3/day per 100 m), reflecting the heterogeneous nature of canal soils, which range from clay loam to sandy loam along the canal alignment. This variation agrees with observations by Bouwer (1978) and Reddy & Kumar (1983) who noted that seepage in unlined canals strongly depends on soil structure, compaction, and groundwater conditions.

The Davis–Wilson, Molesworth & Yennidunia, and Ingham equations give relatively low seepage estimates (5–15 m^3/day), suggesting they may not fully account for the higher permeability typical of sandy loam and alluvial soils found in Ethiopian irrigation canals. Studies by Selim (2024) and Syed et al. (2021) confirm that such empirical relations often underestimate actual seepage in coarse-grained, unlined channels.

Davis–Wilson Method estimated seepage between 5.65 and 11.91 m^3/day, which generally underestimates measured values except in SC4 and SC5. The Moritz method provided seepage losses ranging from 15.94 to 29.66 m^3/day, which are closer to measured and numerical results in sections SC1 and SC2. This formula is particularly suitable for moderately permeable soils, and its predictions align with (Moritz 1952) and (Singh & Sharma 2005), who found the method reliable for sandy loam beds. Molesworth and Yennidunia Method yielded the lowest seepage estimates (3.63–6.49 m^3/day) across all sections. It significantly under predicted the measured losses, indicating that it is best suited for fine-textured soils with very low permeability. Swamee's method produced results between 2.61 and 15.31 m^3/day, again underestimating measured values for most sections. The Ingham method estimated seepage rates between 4.25 and 6.11 m^3/day, showing limited variation. It generally underestimates actual seepage because it neglects lateral infiltration through canal sides (Ingham, 1953). This method is therefore more appropriate for initial seepage screening rather than detailed estimation. The Muskat method predicted the highest seepage rates (12.19–71.59 m^3/day), with closer agreement to measured values in sections SC1 and SC2. However, in low-seepage areas (SC4–SC6), it overestimated seepage. This behavior is consistent with (Muskat, 1937), whose equation assumes higher permeability typical of coarse sandy soils.

The numerical modeling (Seep/W) results ranged from 5.27 to 104.97 m^3/day, closely matching the measured seepage in all canal sections. The good agreement reflects the model's capability to simulate heterogeneous soil layers**,** anisotropy, and seepage paths under realistic boundary conditions. This outcome supports the findings of Mishra (2015) and Kumar et al. (2014) who observed that Seep/W can accurately represent canal seepage behavior when calibrated with field data.

4.4.2. Comparison of measured and estimated seepage by canal Section

Figure 4.1 presents the comparison of measured and estimated seepage losses for six canal sections using seven different estimation methods. The measured seepage values serve as a reference for evaluating the accuracy of the empirical and numerical approaches.

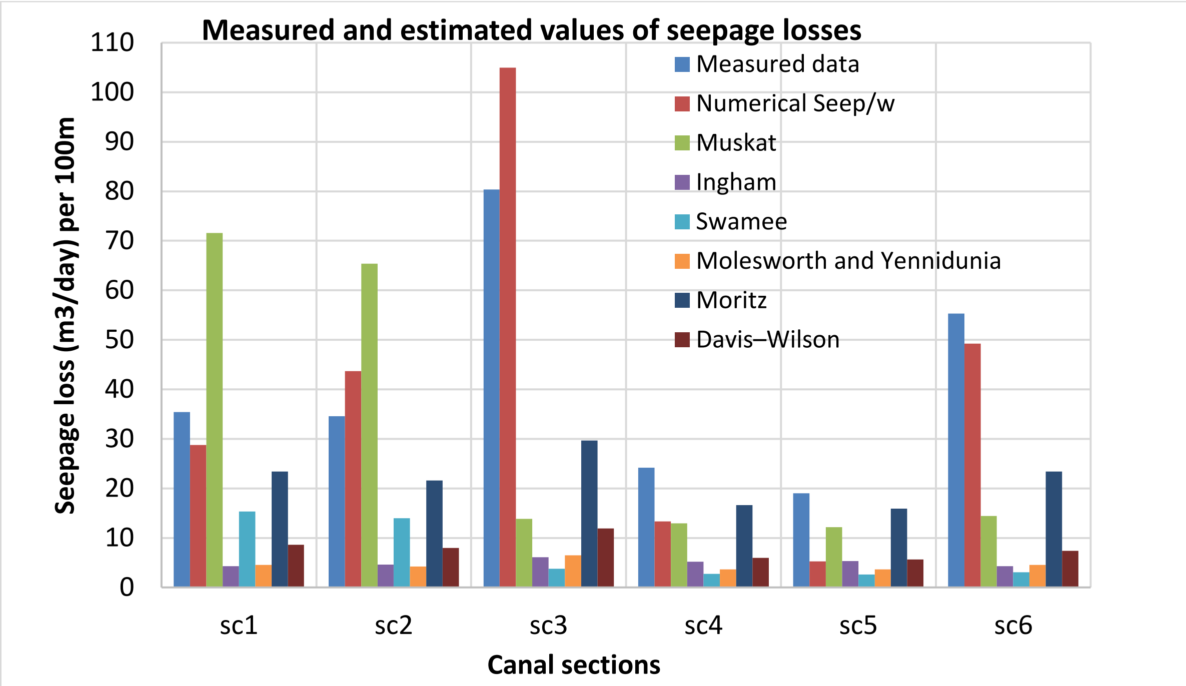


Figure 4-1 Measured vs Estimated Seepage by Canal Section

As illustrated, the measured seepage losses vary from 19.01 to 80.35 m³/day/100 m, with the highest loss observed in canal section SC3 and the lowest in SC5. The numerical model (Seep/W) generally provides estimates closer to the measured data, particularly for SC1, SC2, and SC6, although it slightly overestimates seepage in SC3.

Among the empirical methods, Moritz and Davis–Wilson exhibit better agreement with the measured values, while Molesworth & Yennidunia, Swamee, and Ingham tend to underestimate seepage across most sections. The Muskat method, in contrast, shows significant overestimation in the first two sections, reflecting its sensitivity to soil permeability and hydraulic parameters.

Overall, the pattern indicates that empirical equations provide a useful preliminary assessment but show variable performance across soil and hydraulic conditions, whereas the numerical approach demonstrates higher reliability in replicating field-measured seepage losses.

4.5. Validation of seepage loss estimation methods

To compare the selected seepage estimation methods statistical measures namely, the coefficient of determination (R^2), root mean square error (RMSE), maximum absolute error (MAE), coefficient of residual measurement (CRM), percentage of average error (PAE), and Bias were calculated and their statistics are summarized in Table below.

Table 4-5 Statistical parameters obtained from different methods of estimating seepage from the earthen secondary channels.

Seepage estimation methods	Statistical Parameters					
	R^2	RMSE	MAE	CRM	PAE	Bias
Davis–Wilson	0.78	38.54	68.4	0.81	-78.3	-33.6
Moritz	0.88	25.7	50.7	0.47	-39.93	-19.7
Molesworth and Yennidunia	0.9	41.96	73.86	0.89	-87.4	-36.9
Swamee	0.023	41.12	76.5	0.83	-34.5	-80.1
Muskat	0.039	37.69	66.5	0.24	-7.99	-9.75
Ingham	0.13	41.90	74.2	0.88	-85	-36.5
Seep/W model	0.94	13.25	24.12	0.02	-15.14	-0.69

The R^2 values indicate the strength of correlation between predicted and measured seepage (Figure 4-2). The Seep/W numerical model achieved the highest R^2 (0.94), showing an excellent fit with measured data. Among empirical methods, Molesworth & Yennidunia (R^2 = 0.90) and Moritz (R^2 = 0.88) also demonstrated good correlation, while Swamee (R^2 = 0.023) and Muskat (R^2 = 0.039) performed poorly. The root mean square error (RMSE) and mean absolute error (MAE) quantify deviations between measured and estimated values. The Seep/W model had the lowest RMSE (13.25) and MAE (24.12), confirming its superior predictive capability. The Moritz method performed moderately well (RMSE = 25.7; MAE = 50.7). Other empirical methods such as Swamee, Molesworth, and Ingham showed higher errors (>40 m^3/day), indicating significant underestimation.

CRM values measure the tendency of a method to over or under predicted seepage losses. A positive CRM indicates underestimation, while a negative CRM indicates overestimation. All empirical methods had positive CRM values (0.24–0.89), confirming a systematic underestimation of seepage. In contrast, the Seep/W model (CRM = 0.02) exhibited minimal bias, suggesting excellent balance between over- and under prediction. The PAE and Bias further confirm model tendencies. The SEEP/W model had the lowest PAE (-15.14%) and Bias (-0.69), indicating very small deviations from observed data. Empirical methods exhibited higher negative PAE values (from -34.5% to -87.4%), showing their consistent underestimation of measured seepage.

Among the different empirical and numerical methods evaluated for seepage estimation along the Laelay Wukro unlined irrigation canal, the numerical Seep/W model demonstrated the most accurate and consistent performance when compared with measured field data. Statistical analysis showed that the Seep/W model achieved the highest coefficient of determination (R^2 = 0.94), the lowest root mean square error (RMSE = 13.25) and mean absolute error (MAE = 24.12), and an almost negligible bias (−0.69). These values indicate a strong correlation between the predicted and observed seepage rates, confirming that Seep/W provides a reliable representation of the actual seepage behavior. Abo El-Enien, (2022) applied Seep/W to Ismailia Canal, Egypt, reporting that numerical predictions matched field seepage rates better than empirical estimates. Arshad et al. (2018) reported that Seep/W model has a proper ability to simulate seepage from earthen channels compared with different field analysis methods. This outcome supports the findings of Mishra (2015) and Kumar et al. (2014) who observed that Seep/W can accurately represent canal seepage behavior when calibrated with field data.

The comparison of seepage with empirical equations showed that these equations provides large error in the seepage estimation, although the Moritz's relation with the smaller RMSE (12.356) and higher R^2 (0.373) were better than the rest (Salmasi et al., 2020).

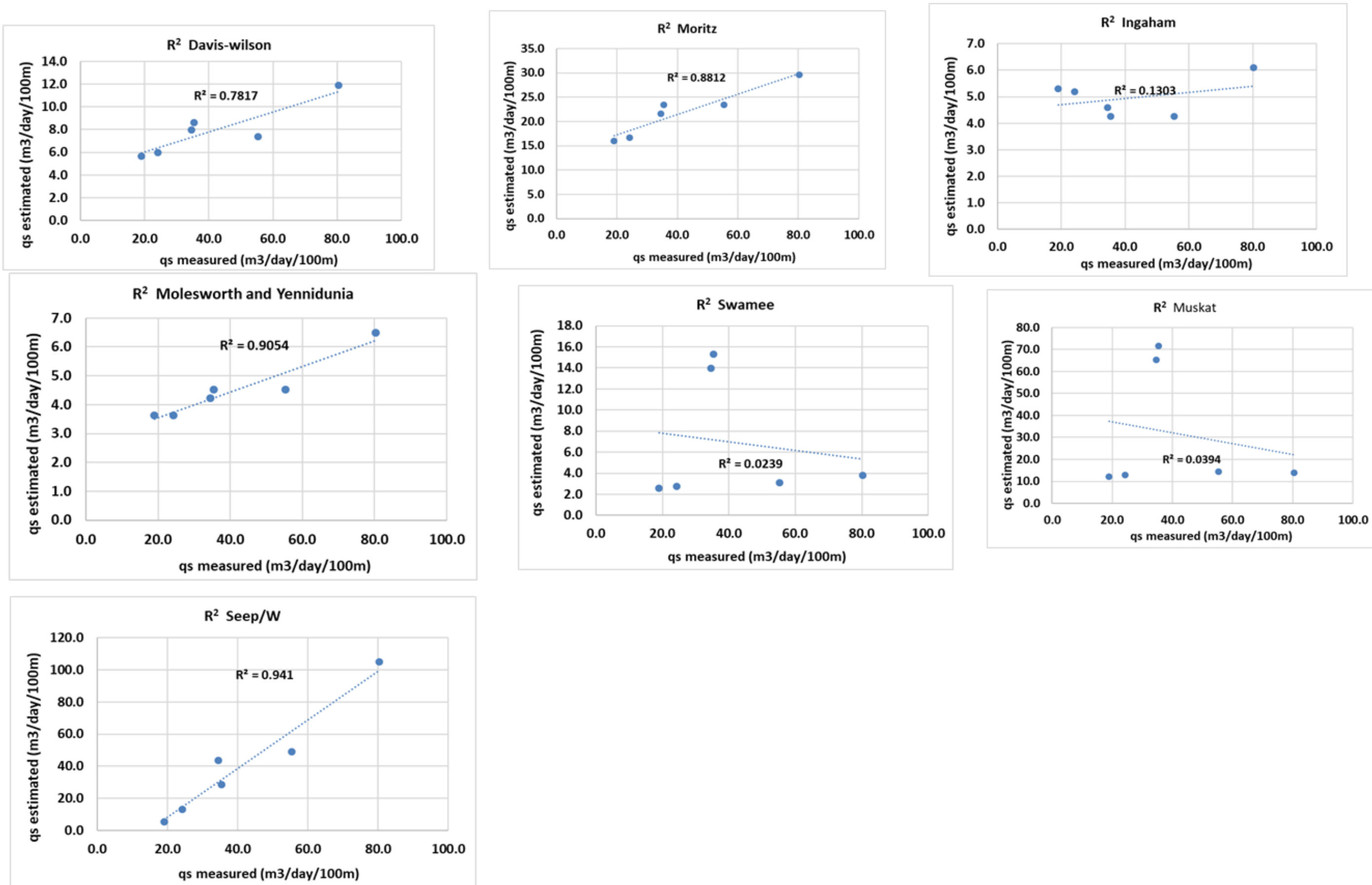


Figure 4-2 Performance of the models using R^2

5. Conclusion and Recommendation

5.1. Conclusion

The evaluation of seepage losses along the canal sections using various empirical and numerical methods revealed significant differences in predictive performance. Based on both the computed seepage rates and the statistical performance indicators (R^2, RMSE, MAE, CRM, PAE, and Bias), the following conclusions are drawn:

The Seep/W numerical model provided the most accurate estimation of canal seepage losses. It achieved the highest correlation with measured data ($R^2 = 0.94$) and the lowest error values (RMSE = 13.25, MAE = 24.12), indicating excellent agreement with field observations. The model also showed minimal bias (–0.69) and near-zero residual mass (CRM = 0.02), confirming its reliability for simulating seepage through heterogeneous soil layers.

Among empirical formulas, the Moritz and Molesworth & Yennidunia methods performed relatively well**.** Both showed good correlation (R^2 = 0.88–0.90) with moderate error levels, although they tended to underestimate seepage losses, as shown by their positive CRM and negative PAE values. These methods can provide reasonable estimates when site-specific calibration is performed. The Swamee, Ingham, Davis–Wilson, and Muskat methods showed poor agreement with measured values. Their low R^2 values (below 0.2 for most) and high RMSE and MAE values indicate that these empirical equations are not suitable for the current site conditions without adjustment.

Numerical modeling (Seep/W) proved to be a powerful and flexible approach. It allowed for a more realistic representation of the canal geometry, layered soil structure, and boundary conditions. The Seep/W results were consistent with measured data, supporting its application for design and seepage control evaluation in irrigation canal systems.

Site-specific calibration is essential for empirical equations. Although empirical methods are easier and faster to apply, their parameters must be adjusted to reflect local soil and hydraulic conditions to improve accuracy.

Overall, the Seep/W model is recommended for future seepage analysis and design optimization. Its superior accuracy and adaptability make it the most suitable tool for evaluating seepage behavior and guiding canal lining and maintenance decisions.

5.2. Recommendations

Based on the results of this study, the following recommendations are made:

- The study confirmed that the Seep/W numerical model provided the closest agreement with measured seepage losses (R^2 = 0.94 and lowest RMSE and bias). Therefore, it is recommended that Seep/W be applied as the preferred seepage estimation tool for unlined irrigation canals in the Laelay Wukro irrigation scheme and similar irrigation projects in Ethiopia and similar semi-arid regions. Since, these models provide more realistic and site-specific results than empirical formulas, which tend to under- or overestimate losses due to their simplified assumptions.
- Since the empirical methods (Davis–Wilson, Moritz, Molesworth and Yennidunia, Swamee, and Ingham) significantly underestimated seepage losses, their application should be limited to preliminary assessments only. For accurate design and rehabilitation planning, numerical modeling supported by field measurement is strongly recommended.
- The measured seepage losses were relatively high in canal sections such as SC3 and SC6, indicating the need for priority intervention. Therefore, canal improvement measures such as partial lining, compaction of canal beds, or the use of low-permeability materials should be considered in these critical reaches to reduce water losses.
- Future studies may extend this work by conducting transient (time-dependent) seepage modeling to account for seasonal fluctuations and irrigation cycles, investigate the interaction between seepage and groundwater recharge downstream of unlined canals and Compare 2D Seep/W results with 3D models (e.g., MODFLOW) for larger canal networks should be studied for the future.

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Appendix

Appendix-1. Tables of Seepage estimation using Empirical formulas

Table 1a Seepage estimation using Davis-Wilson formula

Canal section	C value	Pw(m)	Hw(m)	length (m)	Velocity (V)	Davis–Wilson equation $q = 0.45C\frac{P_w * L}{4*10^6 + 3650\sqrt{V}}H_w^{\frac{1}{3}}$	Seep age (l/s)	m3/day /100m
SC 1	25	0.63	0.18	100	0.352	9.999E-05	0.10	8.6391
SC 2	23	0.63	0.18	100	0.236	9.200E-05	0.092	7.9488
SC 3	25	0.8	0.23	100	0.276	1.378E-04	0.138	11.9050
SC 4	17.3	0.63	0.18	100	0.402	6.919E-05	0.069	5.9780
SC 5	16.36	0.63	0.18	100	0.471	6.543E-05	0.065	5.6530
SC 6	21.4	0.63	0.18	100	0.446	8.559E-05	0.086	7.3946

Table 1b Seepage estimation using Moritz formula

Canal section	C value	velocity(m/s)	canal discarge	Moritz equation $q = 0.0186C\left(\frac{Q}{V}\right)^{0.5}$	Seepage l/se/100m	m3/day/100m
SC 1	0.66	0.352	0.02	2.706E-04	0.271	23.3824
SC 2	0.61	0.236	0.01	2.501E-04	0.250	21.6110
SC 3	0.66	0.276	0.02	3.433E-04	0.343	29.6602
SC 4	0.47	0.402	0.02	1.927E-04	0.193	16.6511
SC 5	0.45	0.471	0.02	1.845E-04	0.185	15.9425
SC 6	0.66	0.446	0.02	2.706E-04	0.271	23.3824

Table 1c Seepage estimation using Molesworth and Yennidunia formula

Canal section	C value	Hydraulic radius(R)	Pw (m)	length (Km)	Molesworth and Yennidunia $q = C * L * Pw * \sqrt{R}$	l/s/100m	m3/day/100m
SC 1	0.003	0.077	0.63	0.1	5.245E-05	0.05	4.5313
SC 2	0.0028	0.077	0.63	0.1	4.895E-05	0.05	4.2292
SC 3	0.003	0.098	0.8	0.1	7.513E-05	0.08	6.4914
SC 4	0.0024	0.077	0.63	0.1	4.196E-05	0.04	3.6250
SC 5	0.0024	0.077	0.63	0.1	4.196E-05	0.04	3.6250
SC 6	0.003	0.077	0.63	0.1	5.245E-05	0.05	4.5313

Table 1d seepage estimation using Swamee formula

Canal section	water depth(m)	Keq (m/s)	wetted perimeter (Pw)	bed width(B)	F=0.35+ 0.65(P/ B)^0.3	Swamee $q = KyF$	l/s/ 100 m	m3/day/100m
SC 1	0.18	8.286E-06	0.63	0.27	1.19	1.772E-04	0.18	15.3106
SC 2	0.18	7.566E-06	0.63	0.27	1.19	1.618E-04	0.16	13.9802
SC 3	0.23	1.600E-06	0.8	0.34	1.19	4.380E-05	0.04	3.7844
SC 4	0.18	1.494E-06	0.63	0.27	1.19	3.195E-05	0.03	2.7606
SC 5	0.18	1.411E-06	0.63	0.27	1.19	3.018E-05	0.03	2.6072
SC 6	0.18	1.671E-06	0.63	0.27	1.19	3.574E-05	0.04	3.0876

Table 1e Seepage estimation using Muskat formula

Canal section	water depth(m)	bed width(B)	Pw(H)	Keq (m/day)	Muskat q(m3/m2/day) $q = \frac{K(B+2H)}{Wp}$	m3/s/100 m	l/se/100m	m3/day/ 100m
SC 1	0.18	0.27	0.63	7.159E-01	0.716	8.286E-04	0.83	71.591
SC 2	0.18	0.27	0.63	6.537E-01	0.654	7.566E-04	0.76	65.370
SC 3	0.23	0.34	0.8	1.382E-01	0.138	1.600E-04	0.16	13.824
SC 4	0.18	0.27	0.63	1.291E-01	0.129	1.494E-04	0.15	12.908
SC 5	0.18	0.27	0.63	1.219E-01	0.122	1.411E-04	0.14	12.191
SC 6	0.18	0.27	0.63	1.444E-01	0.144	1.671E-04	0.17	14.437

Table 1f seepage estimation using Ingham formula

c values	Pw (m)	Hw(m)	(Hw)^0. 5	Lengt h	Ingham formula $q = 0.55 * 10^{-6} CPL\sqrt{H}$	l/s/100m	m3/day/100 m
3.35	0.63	0.18	0.42	100	4.925E-05	0.05	4.2550
3.62	0.63	0.18	0.42	100	5.322E-05	0.05	4.5979
3.35	0.8	0.23	0.48	100	7.069E-05	0.07	6.1077
4.09	0.63	0.18	0.42	100	6.013E-05	0.06	5.1949
4.18	0.63	0.18	0.42	100	6.145E-05	0.06	5.3092
3.35	0.63	0.18	0.42	100	4.925E-05	0.05	4.2550

Appendex-2. Graphs of Canal sections using GeoStudio 2018 R2 (SEEP/W) results

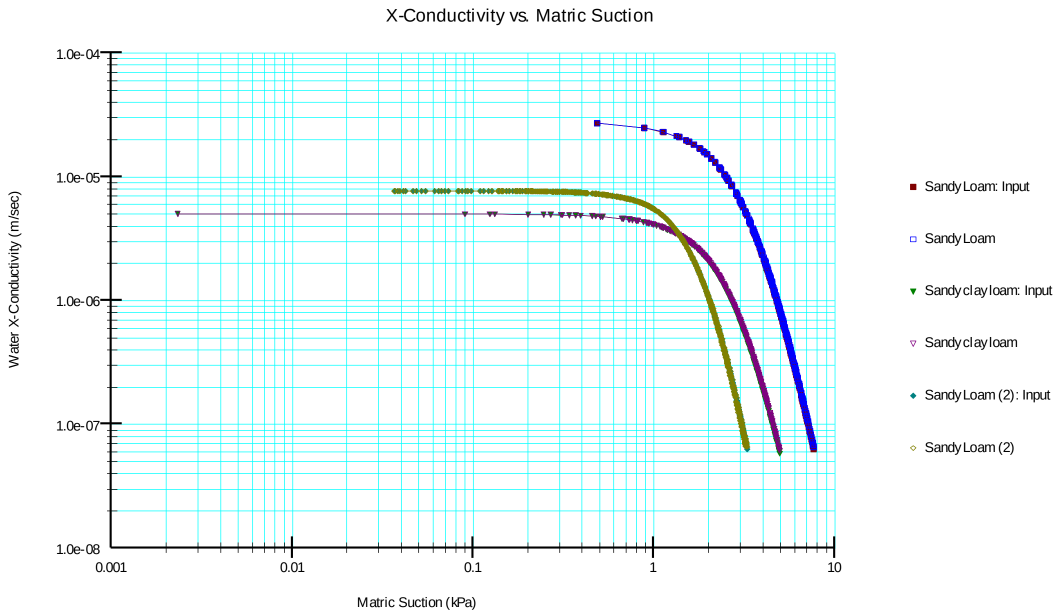

Figure 2a. X-conductivity Vs Matric suction of CS1

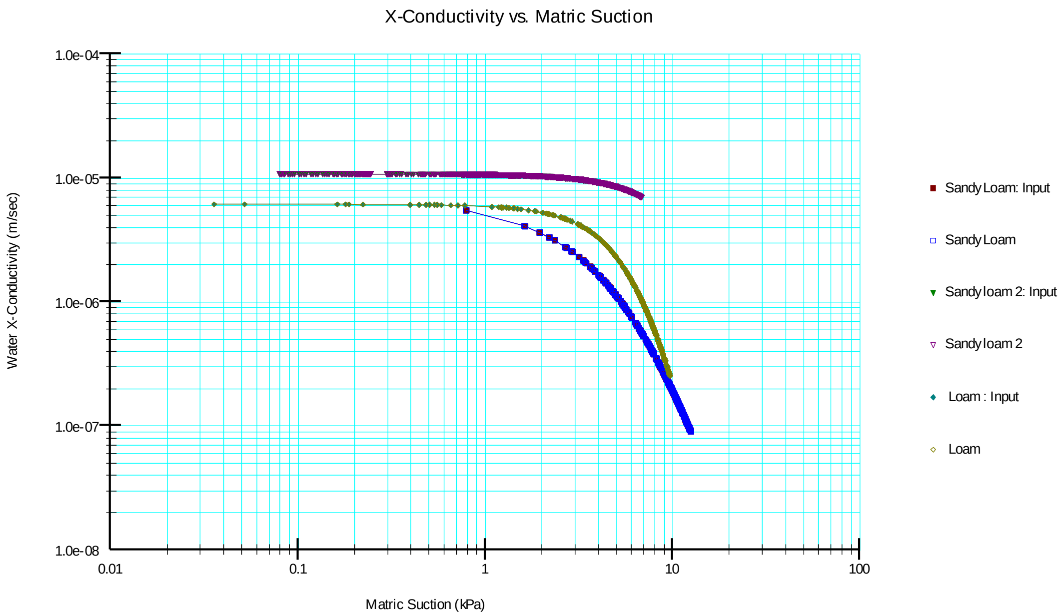

Figure 2b. X-conductivity Vs Matric suction of CS2

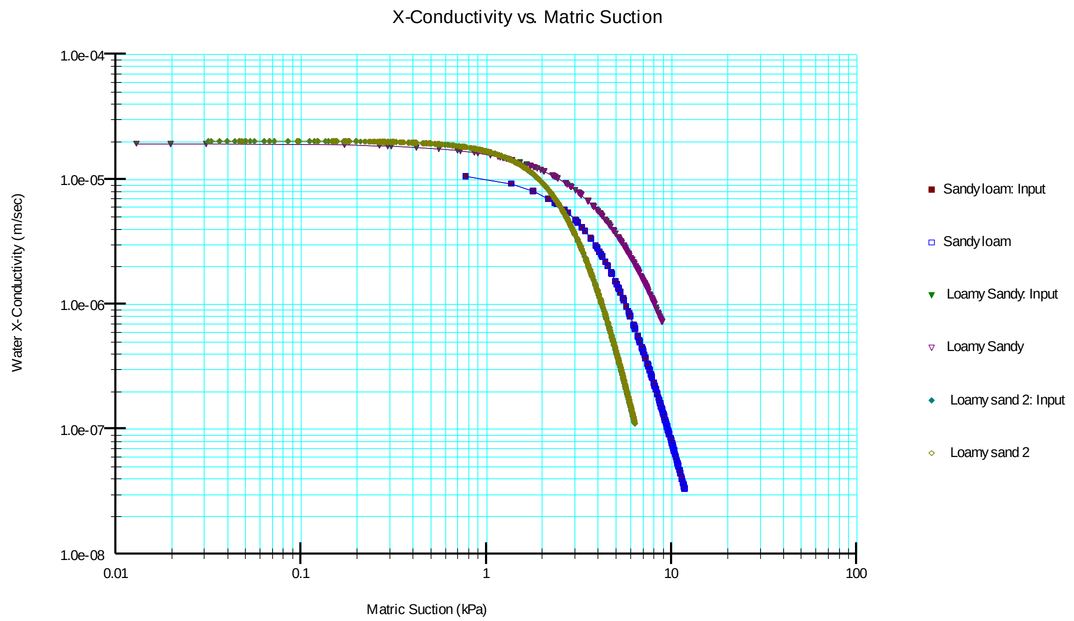

Figure 2c. X- Conductivity Vs Matric suction of CS3

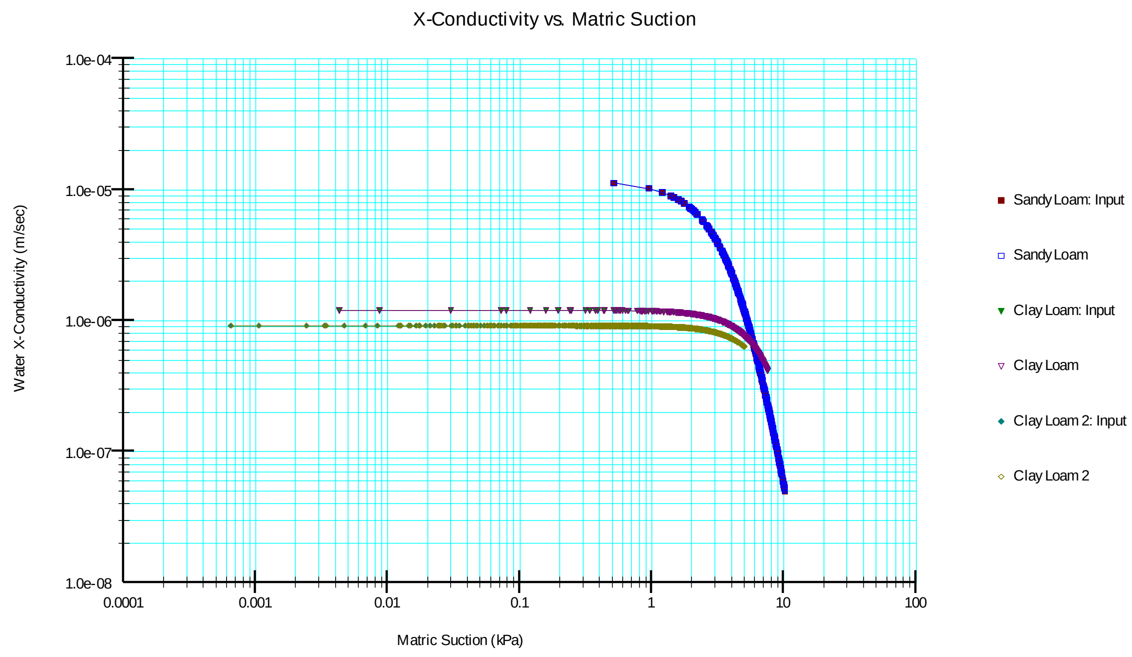

Figure 2d. X-conductivity Vs Matric suction of CS4

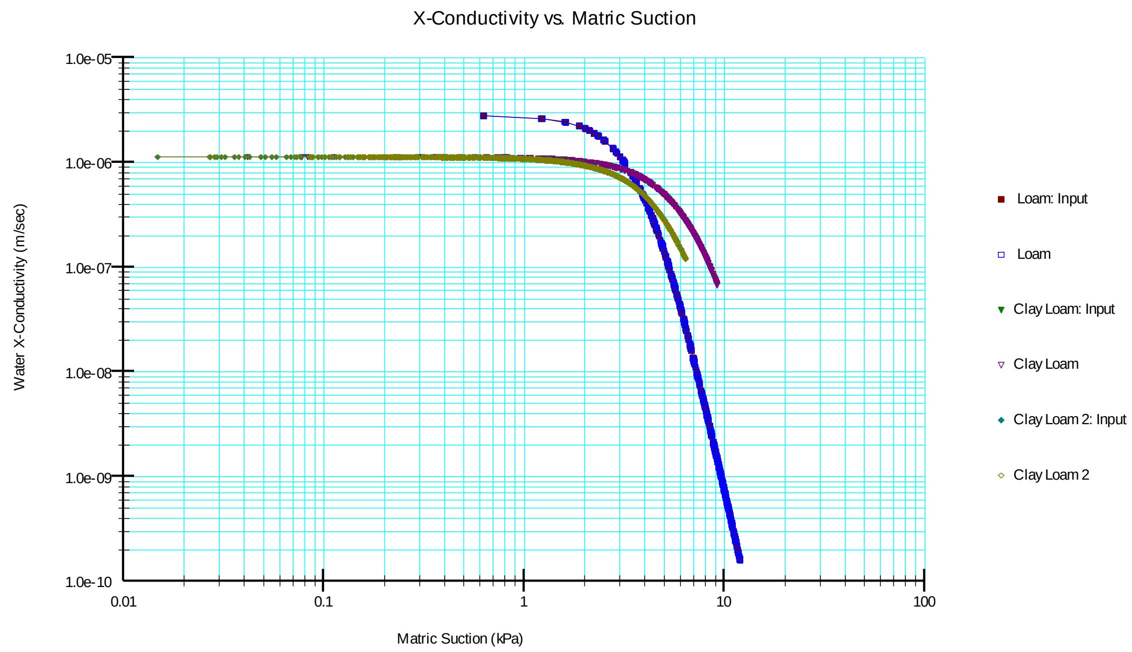

Figure 2e. X-conductivity Vs Matric suction of CS5

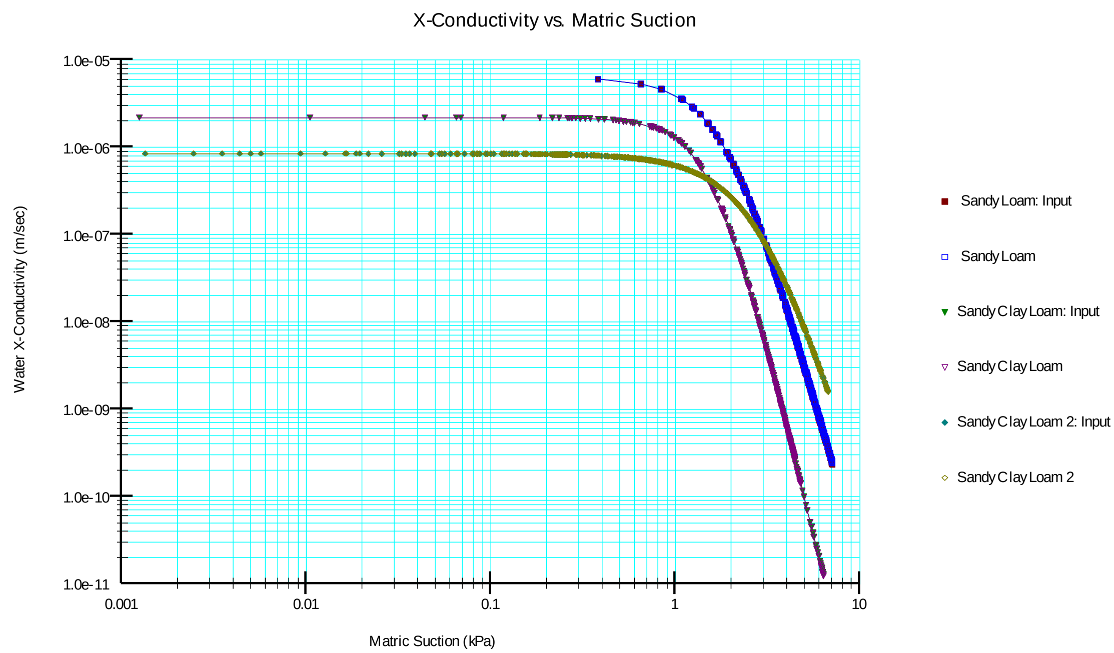

Figure 2f. X-conductivity Vs Matric suction of CS6

Appendix-3. Filed and Laboratory images when collecting data

(a) (b) .(c)

Figure 3a. (a) Soil sampling at the canal bank (b) constant-head perimeter (c) soil textural analysis using Hydrometer at Mekelle university soil laboratory service

Figure 3b. Inflow-Outflow measurement using parshal flume