Development of a Hydrodynamic Model of the Irrigation Canal Network using HEC-RAS. A Case Study of Layyah Canal Division, Pakistan

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No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the department of Water Resources Engineering and Management in partial fulfillment of the requirements for the degree of Master of Science in field of Water Resource Engineering and Management SCEE, National University of Sciences and Technology (NUST), Islamabad.

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5

AUTHOR'S DECLARATION

I **Numan Ijaz** certify that this research work titled "**Development of a Hydrodynamic Model of the Irrigation Canal Network using HEC-RAS. A Case Study of Layyah Canal Division, Pakistan**" is my own work The work has not been presented elsewhere for taking any degree from National University of Sciences and Technology, Islamabad or anywhere else in the country/ world. The material that has been used by other sources has been properly acknowledged/referred.

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7

DEDICATION

I dedicate this thesis to my beloved parents, who have provided me with everlasting love, support, and encouragement.

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In the name of Almighty Allah Who sustains all the living creatures. Man, who is the crown-creature or the superior creature has been endowed with rarest sort of physical, intellectual and spiritual capabilities, is, nevertheless, always dependent upon the mercy of Allah for the successful accomplishment of his ambitions. It is Allah (SWT) who makes our dreams come true. I must also express my gratitude to the last and greatest Prophet Muhammad (ﷺ) whose teachings helped me to weather all sort of crises during my work.

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ABSTRACT

Water is a crucial and fundamental element in irrigation and agriculture. Understanding water dynamics in natural and engineered channels allows irrigation experts to distribute water efficiently. The irrigation canal network of the Layyah Division is critical to supporting agriculture activities of Punjab but faces significant constraints in the operation and management of canals. The main problem in the canal operation is water shortage occurring in the lower Indus Branch supplying water to the Munda Branch. The performance of a canal is determined by its water conveyance efficiency, among other factors. L-Sections (Longitudinal sections) of the canals provide significant details on hydraulic parameters such as canal bed width, flow velocity, Manning's roughness coefficient, and F.S.L (Full Supply Level). However, in most systems, canals are not operated on design discharges because either the canal capacity is insufficient or operated under their designed flow rates. A hydraulic model for a canal is helpful in reproducing practical considerations and operations. The current study represents the development and comparison of a 1D hydrodynamic model of the Munda Branch with a design discharge of 39.5 m^3/s and length of 34.13 km with its 9 distributaries using the Hydrologic Engineering Center River Analysis System (HEC-RAS) and BASEMENT software. Three scenarios were modeled to evaluate the water surface profiles at various cross sections of the Munda: 1. behavior of the canal without lateral and inline structures, 2. the influence of the lateral distributaries, and 3. the impact of inline structures along the canal. Field data and design discharges were used to calibrate and validate the model. The results demonstrated consistent water levels between HEC-RAS and BASEMENT with minor discrepancies. Most of the cross sections of the canal remained submerged under design discharge conditions, underscoring the limiting conveyance efficiency of the Munda Branch. The study highlights the applicability of both modeling tools in design and performance assessment in irrigation systems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

1 INTRODUCTION

1.1. Background and Knowledge

With agriculture being the largest consumer, water use, and allocation becomes critically important (FAO, 2020). The role of agriculture is of key importance for sustaining rural livelihood and ensuring food security and productivity (Molle, 2008). However, different sectors question this due to water scarcity. As the population continues to grow, the competition among different water users increases the dispute over water consumption (Z. Tariq et al., 2023). Open channels and irrigation canals are essential for irrigation schemes, which supply water from their headwater to agricultural lands. To ensure the crop water requirements, these channels are crucial for effective and optimal water allocation and productivity (R. N. Ahmad et al., 2013). Irrigation canal schemes demand assets in respect of regulating the use of water as well as distribution; this embraces distribution of water fairly to user, reduction of losses via leakage and evaporation as well as management of good water systems (Molden, 2013; Viala, 2008).

Punjab Irrigation Department fulfils a vibrant part in the regulation of the water supply and hydraulic structures in Punjab province. Through the effective management of a complex hydrological webs of canals, outlets, and watercourses, PID facilitates water distribution and serves socio–economic production and food security in Uganda. It comprises 26 main canals, 31000km in length and 34000m3/s in discharge capacity of its branches, distributaries, and minor canals (M. D. Ahmad et al., 2009).

(Saeed et al., 2015) stated that the Indus Irrigation Basin System (IBIS) is one of the largest and complicated on which Pakistan's agriculture sector has a hardworking insistence. Today, a number of problems in water management are encountered owing to the fact that the infrastructure of the system has become substantially aged. The system is fully dependent on the flow from the large Indus River but it faces challenge with seasonality and climate change that affects the river flow cycles. As a result of poor and inefficient management practices, the deterioration of this hydraulic structure is resulting into losses of water, and thus water scarcity (Droppers et al., 2022; Qureshi et al., 2008; Wescoat, 1991).

IBIS still employs techniques such as flood irrigation, which leads to low water productivity (Patle et al., 2020). Lack of operation and maintenance, inadequate fund transfer, and inefficient hydraulic infrastructure result in the system's incremental deterioration (Bastiaanssen et al., 2002). Poor water distribution strategies cause tail-end users to receive much less water while head-end users take advantage. This top-down management approach is causing inequity in fair water distribution, causing a significant challenge to IBIS (Shah, 2008).

The outdated water allocation and distribution policies need to be revised to meet the demands of farmers, causing them to breach the *warbandi rules* (fixed water turns), particularly during the critical growth periods (Awan et al., 2016). Additionally, due to climatic variation and water level fluctuations, the traditional rotational irrigation system needs help to cope with water scarcity and uneven water distribution to farmers (Mishra et al., 2001).

Irrigation plays a vital role in agricultural production with specialized techniques to cope with areas having low rainfall or arid zones. Furthermore, to increase the output of agricultural production efficient management of irrigation canal schemes is equally important. In this respect, development of hydrodynamic models for irrigation canal schemes are vital.

The idea of hydraulic modelling has long been used since ancient civilization considering the operation and maintenance of complex hydraulic structure and irrigation canal schemes. Development of mathematical models and principles of fluid dynamics have provided foundations for the modern-day hydraulic modeling tools. For sustainable and efficient practices of open channels or irrigation canal schemes hydraulic modeling is critically important. These models ensure effective water allocation and distribution among its different water users or stakeholders. Simulations could be run under different scenarios and conditions to make sure optimal flow regulation occurs. Development of these models could predict and identify water losses occurring in the canals due to seepage, improper design and evaporation saving water for the consumers.

Hydraulic modeling is crucial for evaluation and design of the hydraulic infrastructures. It supports all the parameters included in the management practices of reservoir, like weirs, gates, outlets and design of hydraulic channels which ultimately leads to optimization and effective operation.

With optimized and sustained applications, the model can promote sustainability and can also reduce the impact of extreme weather conditions like droughts and excess precipitation. It can also mitigate the adverse effects of environment by assessing and predicting the potential impacts of ecosystem. Hydraulic models could give critical data needed for decision and policy making about the infrastructure development, water allocation and distribution for the water users.

Simulated results from these hydrodynamic models could be utilized for the preventive measures of the wear and tear of the infrastructure and reducing the operational and maintenance costs. Furthermore, flexibility in climate change is another aspect given the hydraulic modeling since the water level changes or variations could be simulated using these models.

1.2. Problem Statement

Since food security, the rural economy and infrastructure, agriculture is the most important and influential sector of the Pakistani economy. It contributes nearly 18 percent to GDP of Pakistan, and this shows just how important the sector is for growth and stability. Further, it provides employment to millions of people as the principal source of income to the folks in the rural areas. From this sector, capital is mobilized for financing of rural development needs like physical infrastructure, extension of roads and other better systems of irrigation. Furthermore, this sector holds the greatest potential to answer questions about climate change and its effects. If efficient and sustainability measures and thus resilience were to be incorporated controversies to do with shortage and blurry water future could be solved.

The Division underpins the agriculture of Punjab province, particularly in the river valley region of Southern Punjab. It contains highly developed canal systems as well as number of hydraulic facilities to supply water to the extensive area of landscape. However, it faces challenges which include imbalance water distribution, poor canal development and water leakage among others. Because of these imperfections, the distribution system is inadequate in meeting the water users' requirements and this has adverse impact on the crops yield as well as uncertainty. Control over this aspect continues to be weak due to which a huge amount of water is not only wasted but stolen and there is also a general lack of professional expertise in the management of canals.

To effectively manage the Layyah Canal Division the management and staff require more hydraulic engineers and at least mathematical / hydraulic models for managing the canal schemes.

Moreover, the current operation includes crude and even experimental approaches that cannot cope with present needs. Current practices and paradigms require higher levels of accuracy and detail to model flows and their behavior and require enhancements to overcome the deficits in assessing the changes in water levels and alterability because of climate change. Nevertheless, the department has to become more accurate in data. This seems to call for a fuller copy of data to run the simulation of flow so that good decisions for water sharing could be made.

Considering these challenges, developing a hydrodynamic model that will fulfill the modern-day demands of the agriculture sector is necessary. Layyah Canal Division requires immediate attention and a comprehensive hydraulic model for the simulation, water flow, and operation of irrigation canals. The main objective of this research is to create such a model for the Layyah Division so that contemporary methods can be assessed, and possible improvements made. It will provide an explicit hydrodynamic model for the water flow simulation and a dynamic approach for efficiently managing canals in the area.

Incorporation of the model will help the PID discover the weak areas and the shortcomings in the water resources distribution and allocation system. That is why successful implementation of the further model could help actions to provide adequate measures preventing water losses and distributing water properly. Applying the suggested model in the irrigation canals of Layyah Division shall enable farmers to have an effective tool to initiate decisions, installing resilient techniques and fairly distribute water scarce resources among the farming community.

1.3. Study Objectives

The purpose of this study is to establish a hydrodynamic model of the Layyah Canal Division, due to the complication of the irrigation system in the region. The specific aim of this study is to acre an irrigation scheme of a branch canal and its distributaries. The model will help the PID to know more about fruitful water management practices so that it can efficiently solve the water distribution and allocating problems at the tail-end users of the branch canal. When it comes to standard practices there is an inequitable distribution ratio between the head end user and the tail end user. While head water users get more water than what is fairly distributable, tail water users get hardly any water or the least.

For this reason, special hydrodynamic model will be worked out in HEC-RAS (Hydrologic Engineering Center-River Analysis System), allowing analyzing the specific flows of the complicated canals. The data collection for the model development will involve gathering of data from the irrigation department and then the formulation of simulation based on the acquired field data with a view of measuring the difficulties of the water systems. To add, a geometry of the irrigation scheme, relevant cross sections of the canals, flow rates, and slopes will be constructed using RAS Mapper under HEC-RAS. The flow rates that would have been obtained when the model is simulated will be compared with the designed discharges arrived at from field data to verify the model. In later stages the model will also be calibrated, optimized and validated using the daily discharge data available in DT (Discharge Tables) for various month.

Also, the model will help analyze the complexities of the existing hydraulic structures in Layyah region. It will assess important factors including current operating procedures, amounts of seepage, and effectiveness of the present water distribution model. In this evaluation of the model, it will be necessary to highlight the potential of its developments and the shortcomings of the system. An evaluation report will include recommendation on the water optimization plan to run the canal schemes. It will contain list of possible practices and realistic approaches, which will be used for better water distribution in Layyah Canal Division.

1.4. Significance of the Study

Regarding hydraulic modeling of canal schemes in HEC-RAS there are vast impacts about agriculture, irrigation, sustainability water practices and Agricultural economy in Pakistan. The findings presented in this thesis on the Layyah Canal Division will reveal how HEC-RAS can be applied to complex canal systems. It will show an example of how more complex hydrodynamic models might be employed in hydraulic structures and the foundation with which future research within a similar context could be made. In managing the problems of the chosen sector of the Layyah Canal, this study will add value to the utilization of hydraulic modeling with HEC-RAS. The findings of this research will provide realistic strategies for enhancing the efficiency of the water distribution and allocation system in the canal division. Stating the problems that the system has and pointing at possible solutions will prevent many cases of major losses caused by seepage and evaporation of the water stored in the canals. It will ensure equal and proper utilization of water by the head and tail-end consumers which is crucial in a rise in productivity in agriculture. In addition, it will assist in sustainable irrigation by offering water optimisation and allocation procedures and strategy. Pakistan's agriculture sector is constantly under pressure, as it needs sustainable water resource strategies to cope with issues like climate change and population growth. Improved and sustainable practices will maximize crop yields and address the pressing problem of water scarcity. One essential factor of this research is to develop a comprehensive calibrated model that will serve as a decision-making or policy-making tool for the PID (Punjab Irrigation Department) to implement in other areas of the region. It will provide critical insights into the irrigation system, enabling stakeholders to make feasible water distribution and allocation decisions, supervise infrastructure, and make prospective policy decisions. It is essential to ensure that the decision-making and policymaking are based on comprehensive and reliable data.

Moreover, water scarcity is an alarming issue in Pakistan, including Layyah Division, where adequate water resources and management are integral to meeting the agriculture and domestic water supply demands. So, by illustrating how a complete hydrodynamic model could be utilized to reduce losses and increase water distribution, the study contributes to sustainable water resources and management. Effective and efficient water management practices in irrigation are directly related to the people's agricultural output and domestic prosperity. The deficiencies and improvements proposed in the study will lead to maximizing productivity, increased farmers' wages, and economic stability of the region.

1.5. Scope and Limitation of the Study

The scope of this research is the development, calibration, optimization, and evaluation of the hydrodynamic model of Layyah Canal Division using the Hydrologic Engineering Centre's—River Analysis System (HEC-RAS). The study focuses on the Layyah Canal Division in Punjab, Pakistan, which consists of a complex network of primary and secondary canals used for irrigation. The model covers the entire canal network of Layyah Division, including the main canal, branch canal, and distributaries. It utilizes hydrologic and geometrical data from the government database (Punjab Irrigation Department), field observations, existing literature, and surveys. HEC-RAS simulates, evaluates, and analyzes the flow of water and canal infrastructure in the Layyah Division.

The hydrodynamic model will be derived from the gematric data involving cross sections, discharge, water level, water depth, the external and internal boundary conditions. It will assess the effectiveness and productivity of the current irrigation system coefficients including, water loss, working effectiveness and the effectiveness of the water delivery system. The degree of realism in the scope of the hydrodynamic model shall be confirmed during the verification and validation of the results for the simulation and field/irrigation data retrieved from the PID in the form of DT, i.e., discharge tables.

The objective of this research is to generate an accurate hydraulic model for decorating the Layyah Canal Division while offering an essential knowledge of the same; however, this study has some limitations. The flow and irrigation data and information like the cross-sections of the canal, the most up-to-date discharge tables and boundary conditions: both internal and external to the study area are constrained which imposes the limitations of the hydraulic model in terms of precision and efficiency. In addition, the study is closely associated with the existence of field data that may influence the model's decision/marginal-better assessments of various procedures. Such conditions could explain why the model effectiveness will be restricted as field data is relevant only for the Layyah Division with potential differences from other studied regions. When applied to other areas, climatic variability; and, distribution of water resources and the water distribution patterns also restrict the range of study.

HEC-RAS provides a user-friendly interface that allows users to insert cross-sections of the hydraulic infrastructures, such as irrigation canals, weirs, outlets, and cross regulators so that an accurate depiction of the geometry can be made possible. It calculates the water surface profile under different conditions and field scenarios with variable water flows and geometry. Different hydraulic structures, such as cross regulators (gated structures) and weirs, could be easily managed using the tool to simulate water flow. With the advancements in its capabilities and functionality, HEC-RAS could be employed to run the sediment transport analysis through open channels, making it pivotal for managing water resources and their applications.

1.6. Description of the Study Area

The Layyah Canal Division, which is critically important to the agriculture sector of Punjab, is located in the Layyah district and is included in the Dera Ghazi Khan (DGK) division of Punjab, Pakistan. Munda Branch Canal offtakes from the Main Line Lower Canal (MLL) at (502+000), which receives water from the Indus River. It is located between 30.9634° N and 70.9394° E and is about 150m from the Mean Sea Level (MSL). The topography of the area irrigated by the Munda Branch is predominantly flat and has a semi-arid climate. The district experiences an average rainfall of 200-300mm, with maximum precipitation from July to September in the monsoon season.

The Munda Branch is 34 km long and has a designed discharge capacity of 39.5 m^3/s. The Munda Branch Canal has 9 distributaries which distribute water from the branch canal to the farmlands. The details of all the distributaries emerging from the Munda Branch with their design discharge are provided in Fig 2. Field observation has been taken at RD (1+000) head, RD (112+000) and tail of the Munda Branch Canal. The soils of the region are fertile, with ranges from sandy loam to clay loam, providing excellent features for the growth of crops like rice, cotton, wheat, sugarcane, and maize. The hydrology of the Munda Branch has been heavily influenced with respect to variation in the Main Line Lower Canal, and efficient water management practices are critically important to optimize and distribute water.

Moreover, the Layyah Canal Division comprises complex irrigation canal schemes, including the MLL (Main Line Lower) Canal, Munda and Indus Branch, and their distributaries fed by the Indus River, the region's primary water source. The Indus feeds the central portion of water to canal schemes, which further transfer the water to agricultural fields. The Main Liner Lower (MLL) canal is the large canal that regulates the water flow into branches (Munda and Indus).

These secondary canals distribute the water to the minors and distributaries such as Pir Chattar and Inayat. These smaller channels control the water for fields and farms throughout the Layyah region. Own hydraulic structure of the water flow includes weirs, canal falls and outlets which will be used to effectively dispose water and also reduce wastage of water.

Moreover, the Layyah Canal Division has contribution to the regional economy directly related to agriculture and population's living standard. Agriculture is practiced by most of the people, and the city's total population is fairly estimated to be 1.5 million. So, the central portion of the region's economy relies heavily on agriculture, with major crops including sugarcane, cotton, and wheat. The irrigation schemes support irrigation, which is vital for maintaining the economy and food security. A greater population relies on farming and agriculture; hence, water management is very crucial for the inhabitants of this region. This is topical for the support of the crops and maximum yield in agricultural land, that requires fair distribution of water and availability of water is climactic.

The Layyah Canal Divison involves a complicated system of irrigation and faces many problems like Quality Distribution of water, Water Losses: leakage, seepage and evaporation. It comprises many hydraulic parts, outlets, canal lining, weirs, head regulators, and canal falls that are useful in the administration and distribution of water. Therefore, it becomes important to understand the water level changes, modified by global climate change and river fluctuation, to avoid losses through seepage and to plan and implement water management regimes efficiently. Any defects appreciated and possible ways to maintain and effectively utilize hydraulic structures can be Localized, therefore, determination Of these flaws and strengths for the management of water supply, structural repairs, and longevity of the natural resource is inevitable.

1.7. Overview of the Methodology

This research identifies the step by step approach to Hydrodynamic modelling of the Layyah Canal Division in HEC-RAS. This comprised a several phases including field data collection phase, model construction phase, model estimation phase, model refining and validation phase. Since it uses both quantitative and qualitative data, it adopts systematic type of research approach to ensure that a comprehensive hydrodynamic model is established. The data-gathering process involve field surveys, cross sectional data (geometrical data), and hydrological data to develop detailed and up-to-date hydrologic model of Layyah Canal Division. The cross sections, velocity, and discharges are measured directly and critical parameters are easily obtained. Useful information on geometrical and flow characteristics of the canal exists in the data continuously received from the PID, a government body.

The collected data, including canal geometry (cross-sections), flow rates, and channel depth with boundary conditions, are then fed to the HEC-RAS to develop the model. The model will then be calibrated according to critical parameters such as Manning's roughness coefficient 'n' and discharge coefficients. The model is developed to configure 1D steady flow analysis to give critical insights into different scenarios. The model is simulated with different conditions and scenarios, which shows how the model responds to different systems. In the validation phase, the simulated water level and discharges from the model are compared with the field or observed DT (Discharge Tables) obtained from the Punjab Irrigation Department.

1.8. Thesis Layout

1.8.1. Chapter 1 (Introduction):

Briefly describes the background and overview of the research, defines the problem statement, objectives and scope of the research and preview of the methodology.

1.8.2. Chapter 2 (Literature Review):

Provides an overview of the hydrodynamic modeling, HEC-RAS, application of HEC-RAS to canal modelling.

1.8.3. Chapter 3 (Methodology):

Describes the details of research methodology used in this study.

1.8.4. Chapter 4 (Results and Discussions)

Provides details of the results and discussions of the simulations under different scenarios in HEC-RAS 6.3.1.

1.8.5. Chapter 5 (Conclusion and Recommendations)

Discusses the conclusions of the simulation run by the hydrodynamic model on HEC-RAS, BASEMENT, and possible recommendations.

CHAPTER 2

2 LITERATURE REVIEW

Hydrodynamic models are crucial for managing and comprehending the behavior of irrigation canal schemes (Fao, 2008). They copy the movement of water through open channels and assists in the evaluation of hydraulic environment of the canal structures. Theses models are formulated from the laws of conservation of mass and impulse set by continuity and fluid dynamic equations. As for the simulation of the water flow, one can use the following techniques: 1D, 2D, 3D, whereas 1D techniques are more preferable, as simple and effective. Hydrodynamic models play a very important role in planning and operation of waterways for proper distribution and management of the water. Generation of hydraulic models might be useful in evaluating the flow capacity of open channels such as irrigation schemes and effectiveness of water conveyance to the field (Kamran et al., 2021). They are important tools in providing quantitative and qualitative details of where changes can be made, enhancing water use efficiency and minimizing wastage through seepage and the other key factors.

2.1. HEC-RAS

HEC-RAS (Hydrologic Engineering Center-River Analysis System) is one of the most used tools in the hydraulic modeling. It is commonly used to create flow and analyse hydraulic structures. The U.S. Army Corps of Engineering created the hydrodynamic modeling software or other water resources simulations such as flood simulations, flood risk mitigation, and best allocation of water resources. Firstly, the software was created in 1995 to generate 1D models of artificial open channels. Over the years, the software has evolved and gone beyond offering two-dimensional modeling to include three-dimensional modeling. It has numerous valuable features that enable 1D hydrodynamic modeling and it is characterized by an easy-to-use interface. Relative to the other methods of modeling open channels, it is relatively easy to learn and further model thanks to the GUI or Graphical User Interface. They help the user to analyze data, visualize it and manage it thus plays a vital role when in a tough hydraulic situation or when handling field data by the hydraulic experts and the engineers.

It was found earlier that HEC-RAS can simulate water with steady and unsteady flow states using fixed and variable discharge data. The geometric section enables the users/engineers to easily and quickly edit and input geometric data using cross section of the channels. RAS Maper could be utilized to create different layers for terrain models, which could be combined with other terrain data to give water surface profiles and velocity profiles within the boundary layers.

Due to its variety of modelling options, user-friendly interface, and ability to simulate the water flow under different scenarios, HEC-RAS found its valuable applications in irrigation canal modelling and schemes. Attributing the development of canal modelling, engineers/hydraulic experts could utilize the software to enter the geometry of the open channels, extract results in the form of rating curve hydrographs, and predict the water surface profiles. Its most important and primary function is to equip the engineers to simulate water flow and predict the behavior of water under different scenarios such as drought and extreme precipitations. It could model both steady and unsteady flow data, solving the intricate issues of engineers. Dealing with the steady flow data, HEC-RAS can be used to compute the water surface profile of discharge at a constant rate. Similarly, unsteady flow data could be employed for discharges with variable rates. HEC-RAS could be employed to analyze the hydraulic behavior of irrigation canals with complex infrastructures, predict water level fluctuations, canal breaches and flood risk management. It could be utilized to model canal schemes to ensure optimal water distribution and allocation.

HEC-RAS could be employed to model irrigation canals with different hydraulic structures, which allows the model to analyze the hydraulic behavior of canals, sections, or reaches with sedimentation and low flow capacity. With the identification of certain challenging sections or reaches, the model could be utilized to suggest possible remedies. One of the features of this tool is to include hydraulic structures such as (Weirs, outlets, and falls), which are crucial for the detailed and comprehensive analysis of the complex schemes. The efficiency with which the gates of these hydraulic structures are modified in HEC-RAS is vital for water distribution and management for the engineers.

The variety or diversity with which HEC-RAS allows the user to input data makes this modeling system unique. The set of components involving Manning's equation and momentum equation make it useful for the analysis of rapidly varied flow.

The effects of hydraulic structures such as dams, weirs, and culverts could be easily computed using the software. Some special features include unsteady flow simulations, multiple profile calculations, and design, as well as analysis of the open channels and river systems. The innovative user interface shows various approaches to creating and erasing multiple projects.

HEC-RAS has broad application capacities, including steady flow hydrographs analysis as well as twine modeling and simulation of complex channels. In steady flow analysis, detailed solicitations of the water flow are made based on steady flow and situations and thus offering hydraulic design and capacities data. On the other hand, the unsteady state uses computation under conditions that fluctuate, and engineers can gain insight into the uniqueness of the flow and the hydraulic structures' design. Due to the certain extraordinarily comprehensive functions and capabilities listed above, HEC-RAS is now one of the most important engineering tools in the field of water resources and management practices.

HEC-RAS can analyze wide flow hydrographs in addition to twine modelling and simulation of complicated channels. In steady flow analysis, precise petitions of the water flow are established based on steady flow and situations and thus provides hydraulic design and.competency datum. On the other hand, such a state applies computation under conditions of instability, where engineers are able to look at the distinct flow and the configuration of the hydraulic structures. Because of the above certain extraordinary characteristics of the functions and capabilities for individual HEC-RAS application the program is recognized as one of the most important engineering supports in water resource area and management practices.

HEC-RAS is a complete software developed by the United States Army Corps of Engineers also known as USACE. The development of HEC-RAS brought with it a very good platform for the hydrologists and engineers in computation of hydraulic characteristics of water channels at different circumstances. The evolution of HEC-RAS could be traced back to the arrival of mission of USACE in performing hydraulic activities that include hydrodynamic modeling, flood risks, and water resource applications. As far back as 1960, HEC 2 was designed for the purposes of steady-state simulation and for the determination of water surface profiles.

While it had some drawbacks as for the point of view of its practical user interface it was a pioneer tool in the field of hydrology and water resources and served as a basis for further improvements and enhancements. After this, to perform steady and unsteady flow calculations, the need of more advance tools was realized and HEC-RAS started changing.

The first version of the HEC-RAS began in 1995 as a hydraulic modeling tool in hydraulic design. When developing the idea of the mentioned tool, its purpose was to create a tool for the steady and unsteady state simulation. It allowed users' simple operation, and it could be used for both steady and unsteady flow studies through GUI for achieving effective model and data solution.

Since the innovation of HEC-RAS, there are significant changes and technical improvements to the functions of the application. In 1997, HEC-RAS version 2.0 was released complimented by sediment transport analysis, as well as enhanced data management and simulation. In the following year 2001, the third and more enhanced version of the program was launched having more unsteady state simulation feature of more complicated and elaborated systems. Rich set of features of Version 4.0 provided for the modeling of complex relief and hydrotechnical structures. Further, new in this current HEC-RAS 4.0 was the inclusion of 2D hydraulic modeling that provided more rapid and accurate computations concerning flood plains and terrains.

Likewise, versions 5.0 and 6.0 have central updates linked to 2D modeling and better meshing with bypassing real-time predictive instructions. The new and enhanced version comes with many examples of boundary conditions and complicated hydraulic structures. Each of these evolutions has technically added more functionality and capability to the HEC-RAS software. GUI has made data entry, data management, and the way data is presented easier, providing GIS and 3D rendering integration. In terms of efficiency as well as precision of hydraulic operations, time-step or adaptive processing has improved over time. The addition of 2D and 3D modelling capabilities means that engineers and hydrologists are able to perform a greater degree of modelling and analysis at seemingly little extra effort.

Integration of HEC-RAS with GIS has enabled the user to work with high resolution data, more computational choices and added levels of accuracy. In terms of dynamics the software has evolved its ability to handle sediment transport analysis, sediment dynamics and the impact of sediment transport on channel form.

These influence the wide range and capabilities of HEC-RAS to projects, with a deep impact on irrigation and water resources. It is valuable in flood hazards forecast and management practices due to it flexibility in modeling unsteady flow and compound hydraulic channels. It could easily be used to employ computational approaches with hydraulic structures like; culverts, weirs, dams and bridges with regards to channel regime in view of certain scenarios.

2.2. Hydrodynamic Modelling with HEC-RAS

HEC-RAS could be used to analyse flood risk for irrigation canal of open channels. Engineers can model the water in the environment to determine effects such as those that might make canal reaches dangerous. Likewise, deciding overtopping risk and breach calculation in HEC-RAS can be beneficial for the adjacent agriculture land. For example, in Naramda, India, the software has been employed to discharge the arduous and elaborate irrigation system. Using HEC-RAS, the impacts of several hydraulic structures related to sediment transport were explored. The assessment of contribution of the Narmada project becomes very important in the context of the research done on the water management practices in the region.

Furthermore, HEC-RAS is being applied to analyze complicated irrigation canals in Egypt including the main subjects of this research. Due to this and the wide spectrum of tasks it solves, engineers use it to both design hydraulic structures and analyze events such as canal failures and floods. The engineers were able to get better understanding of the canal dynamics and the impacts of different variables on the flow and depth of the flow from HEC-RAS. From the outcome of the analysis that has been conducted on those, they were able help improve the efficiency and the sustainable water usage in Egypt. Furthermore, the features of HEC-RAS within this context remained beneficial for the best strategies of water supply.

It was also noted that steady and whenever needed unsteady flow data could also be simulated using HEC-RAS. For example, a model was surveyed on the Hakra Branch Canal of Pakistan with reference to inconsistency in the share that is allocated to head and tail end users. To determine the hydraulic performance of the Branch Canal, designed data of the geometry of the Branch canal and various inline and lateral structures were used.

Finally the validation which was done in two ways was achieved by comparing the irrigation data/field data obtained in the form of Discharge table (DT) and simulated discharges using other software HEC-RAS. These simulated results are beneficial in identifying the loss in canal and expected flow for downstream users of the Hakra Branch Canal (Kamran et al., 2021).

In addition, HEC-RAS could be more practiced and compared with other networks like, ANN (artificial neural networks), and FIS (fuzzy interference systems) for the distribution and optimization of water. A similar study was done to canals' water distribute systems, targeting an initial focus on intelligent networks and their connection to HEC-RAS. To build the model for the study, the researcher gathered appropriate and detailed information concerning the geometrical characteristics of the canal, flow and other features of the canal that may influence the systems behavior. The model was applied to estimate the hydraulic behaviour of the canal system and FIS approach was applied to quantify the risks associated with the system. Navigational benefits were achieved by incorporating HEC-RAS with other leading intelligent models to raise the total performance of the canal undertakings. The outcomes supported the developers who offered a decision-supporting system, which could be used later for maintaining and improving water distribution in the constructed canals (Sharifi et al., 2021).

It had been possible to predict the hydrodynamics of river and open channels, their hydraulic behavior and extents of flood using HEC-RAS with GIS data. For example, a parallel style of research work was carried out in the Periyar River in which a geometric file of the river was prepared and put into the software to observe the flood in different condition. Boundary conditions were represented using water level and flood hydrographs. Thus, additional testing and calibration of the model were performed using the data obtained, which proves the effectiveness of the model. The results simulated from the HEC-RAS model were superimposed with GIS to create floodplains and find the flood prone zones. Hypotheses of the research were incorporated to show the hydraulic characteristic of the levees and the flood barriers. In particular, understanding the details of flood-prone areas and river hydromorphology enables improving the effectiveness of water resource management.

Furthermore, the hydraulic parameters could be used to assess the sensitivity of the hydraulic parameters by using HEC-RAS. The efficiency of irrigation and drainage works could be improved by searching detailed information on the impact of various parameters in HEC-RAS.

(Shahrokhnia, 2024) have also conducted similar research on Doroozan irrigation systems when geometrical data was collected to model the cross section of the canal. These values were based on flow data and normal depth at U/S and D/S for the setting of steady state boundary conditions for simulation. In calibrating the HEC-RAS model, Manning's roughness coefficient and other coefficients were fixed in order to match the design discharge of the channel. With the help of these results they were able to determine where most likely mutations are necessary.

The flood behavior of a particular reach can be modeled by the HEC-RAS for estimation of flood events. In HEC-RAS software, flood characteristics of the Phang River were analyzed based on a 1D hydrodynamic model. The model draws geometry from the river cross-section shown where information from the riverbanks and floodplains are obtained from. Specifications to boundary conditions were made with the help of flood discharges and depth of the water. Given flood hydrograph and rainfall, the model was calibrated. For model validation optimizing Manning's roughness was done to achieve the best estimates. The model supplied the functions of getting to the areas of flood that was important in the risk management involving flood (Zainalfikry et al., 2020).

Additionally, HEC-RAS can analyze the contaminants and sediment in the river system. For example, (Shabani et al., 2021) utilized the software in couple with WASP model to predict the sediment transport for the water quality purposes. Based on a 2D hydrodynamic model in HEC-RAS, flood simulation demonstrated how the interaction occurred between water depth and velocity in the floodplains and for more accurate analysis and a pair of 100-year and 500-year data were applied to check model calibration to produce the specific outcome. In contextualizing flood contamination simulations, WASP (Water Quality Analysis Simulation Program) was acquired. The comparison of the calculated results of the model with the measured values helps to find the uncertainly about water surface fluctuation as about 0.09m, so the higher level of precision is necessary in the given study.

The performance of water distribution in the agriculture network could be evaluated by HEC-RAS in combination with other hybrid models. (Kaghazchi et al., 2019) used the same technique in which a combination of hydrodynamic models in HEC-RAS and HBN (Hybrid Bayesian Network) was utilized to simulate and evaluate the performance of irrigation networks in Iran. A detailed hydrodynamic model of the irrigation canal network was developed with the collected data from the field and calibrated with the help of historical data. The assessment of the model was carried out with key performance measures, including optimum, equitable and efficient water allocation. The result obtained proved that the model effectively modeled and analyzed the flow in the canal system. It effectively improved the appraisal of the agricultural water distribution systems and gave direction to future similar studies.

HEC-RAS could be operated to improve fundamental hydraulic variables such as the Manning's roughness coefficient for the hydraulic channels. For example, a similar type of research uses the integration of HEC-RAS model with PSO (Particle Swarm Optimizer) in which the channel resistance is being simulated by adjusting the Manning's n value. The model was built basing on the input of channel cross-section and geometry of the channel. Here the unsteady state simulation was for the flow rates and the water depth in the channel. After developing the model calibration was achieved using PSO with Manning's n between simulated and collected data. As a result, the optimized n values were used to control the inconsistency in the various hydraulic structures at a later stage. As seen from outcomes of the analysis, with the optimizing technique, the possibilities to raise its precision up to a significant value are provided (Shahverdi & Talebmorad, 2023)..

The impact of hydraulic structures proves to be instrumental in the efficiency of the water distribution system. (J. A. Tariq & Latif, 2011) did parallel research with a primary focus on simulating the outlets of the irrigation canal network. The HEC-RAS model for evaluating the performance of outlets under different flow conditions and scenarios was developed. The model is calibrated using the historical flow data with the boundary conditions The hydraulic performance of outlets is assessed using 1D steady-state simulations and the results are concluded here. A power outlet's flexibility and efficiency were determined based on functionality according to water distribution efficiency. These analyzed findings regarded this revelation that the outlets with gates, and automation of the operations showed minimal water losses. This way, with methods of optimal distribution of water available the hydraulic capacity of the outlets could be enhanced to enable the development of more resilient form of irrigation systems.

(Purboseno et al., 2021) used HEC-RAS to analyze the hydraulic behavior of irrigation systems involving flow dynamics and behaviour within reach of the Dadahup Swamp Irrigation Area (DIR) in Kapuas Regency. The development of the model involved creating the geometry in HEC-RAS with observed data gathered from surveys done in the fields. Internal and external boundaries in HEC-RAS were set using topography and the outer boundary of the DIR.

An hydraulic assessment of the swamp area which complicates the irrigation system was conducted and modeled in HEC-RAS. To assess water level changes in the system, an unsteady state simulation was also performed. These simulated results were used by the local government authority to facilitate the identification of flood risk techniques.

Various kinds of research have revealed that the form of construction and management of irrigation canals discriminates in favor of the head-end farmers and they receive unrestricted water supply even though water demand is low. Because of poor control and management, this scattered water supply becomes worse as it reaches downstream tail-end farmers. Such imbalance in water means that tail-end farmers are either to reduce their area under cultivation or struggle with low yield from the crops they produce. It directs the farmers with average or little water supply to adjust the gates and outlets which triggers legal battles (Shah, 2008).

As a result of these disparities and to ensure that water is distributed in the proper ration, it is important that hydraulic modeling of the irrigation systems is useful. These hydrodynamic models are useful in governing the complex irrigation networks, and give insight into the hydraulic conditions of the canals and distribution of water in an acceptable manner. (Islam et al., 2008) pointed out that the identification of hydraulic behavior of canals through hydraulic modeling is also important. The researchers also used HEC-RAS to create a hydraulic simulation model to determine the effectiveness of Right Bank Main Canal. The calibration of the model was done with the observed data, and it has been possible to implement simulated results to the canal network. (Khan & Ghumman, 2008) compared the observed data of the canal with simulated results from a CanalMan model that was used to determining the hydraulic behavior of minor irrigation schemes. The 1D hydrodynamic CanalMan model results were successfully implemented in the problem of uneven water distribution between the head end and the end users at the tail end.

(Mandavia, 1999) applied canal automation approach to resolve the canal head and tail end user for the canal system in India. The findings of the study suggest that poor control over the canals, which must be manual because of their age, results in water wastage and water segregation between the users. Usually detail cross sections or geometry of the canal are inadequate, and normally data collected is not accurate due to effects such as sedimentation and siltation.

The longitudinal sections (L-Section) of the canals and design parameters must be adjusted accordingly to meet the demands of tail-end farmers.

Therefore, hydrodynamic modeling for canals is valuable in optimizing water allocation and canal operations. (Serede et al., 2014) carried out research to determine the discharge potential of the irrigation canal in Mwea, Kenya using HEC-RAS and it is established that the simulated results of the model can be used appropriately in the study of the hydraulic characteristic of the canals.

(Kamran et al., 2021) formulated an unsteady flow model in HEC-RAS on the Hakra Branch Canal Pakistan udized the canal inequality between the heads and tail-end consumer. Based on the designed hydraulic data of the Branch Canal, inline and lateral structures' hydraulic design parameters were input into the hydraulic modelling to determine the resulting hydraulic behaviour of the Branch Canal.

The model was validated through a comparison of irrigation data or field data in the form of a discharge table (DT) and modeled discharges from HEC-RAS. These simulated results are important to note the losses in the canal and the expected flow to convey them to the downstream users of Hakra Branch Canal.

The main objective of this study is to perform hydraulic analysis of the Munda Branch Canal in Layyah Canal Division through HEC-RAS. It incorporates calibration of the simulated discharges with designed discharges/full supply level, optimizing the inline and lateral structures, controlling the pond level/FSL in the respective distributaries and minor canals and offering an enhanced information platform for the PID Layyah for better water distribution to farmers.

2.3. Hydrodynamic 1D Modelling of Irrigation Canals with BASEMENT

BASEMENT is an open-source software developed at ETH Zurich mainly for hydrodynamic and morphodynamical modelling. It can also be practically used for river flow, floods, and sediment distribution without core modification. A complex numerical solver has been adopted within the software for 1D hydrodynamic modeling that uses the Saint-Venant equations or the shallow water equations. This approach is highly relevant to systems where the flow direction is mainly one way, for example, river, streams and canals.

In one-dimensional hydrodynamic modeling, the BASEMENT calculates flow characteristics like water depth and velocity perpendicular to the defined channel center line, thereby lowering the computation requirements without compromising on the overall applicability in a few engineering and eco-hydrological applications.

Modelling with Basements includes the following advantages:

- Users are also to specify boundaries and geometries of the channels to obtain very close to natural or artificial channels.
- The software can handle different boundary conditions, for instance in inflow hydrographs, the outflow rating curves and even lateral inflows.
- For solving non-linear flow equations, BASEMENT applies schemes of numerical solutions that perform stability and accuracy irrespective of high steepness or quick changes in dynamics.
- The software is designed to enable linking 1D simulations with either 2D or morphodynamical ones, which lay the foundation of rather integrated approaches.

Specifically, the 1D module of BASEMENT is effective in approximating the distribution of canal systems. Such networks are often made up of more or less row-like, strict, one-directional links with limited throughput and therefore are well-suited for 1-D analysis. Developing hydrodynamic model in BASEMENT involves the following steps involving outline of the canal by describing the features of cross section, longitudinal gradient as well as the size of the canal. These parameters are important for flow characteristic determination, especially in different operating conditions.

- For irrigation canals boundary conditions pertaining to upstream nodes may be an inflow rate while for downstream nodes it may be a water level. Power initialization conditions are also set such as base flow, empty canal and so on.
- Components of the irrigation system like gating, weir and culvert are included in the model to enable regulation and distribution of flow.
- Computation of operations in BASEMENT can control instructors to mimic practicability of operating scenarios for irrigation such as the gate opening or the discharge, characteristics that increase comprehension of irrigation distribution.

- It is refined using field data of flow rate, water levels and open/close status of gates in the system. This step places the simulations in an area whereby the results obtained from the simulations are very close to actual behavior.

A precise emulation of water delivery and distribution is achieved through BASEMENT's numerical algorithms that portray water flow in kept environs. The software also has the advantage of modeling different geometries of the canal and hydraulic structures using the situations that require irrigation. When used in connection with 2D or sediment transport models, the model is able to address problems of sediment deposition, erosion, and flood along the canals. Applying the BASEMENT for the 1D hydrodynamic modelling of irrigation canals improves the performance of the assessment and planning of the water distribution, the efficiency of the system, as well as the prospective developments. This approach is ideal in giving scientific underpinnings of sustainable human and natural resource management, particularly irrigation.

CHAPTER 3

3 METHODOLOGY

3.1. Description of the Study Area

The Layyah Canal Division, which is critically important to the agriculture sector of Punjab, is located in the Layyah district and is included in the Dera Ghazi Khan (DGK) division of Punjab, Pakistan. Munda Branch Canal offtakes from the Main Line Lower Canal (MLL) at (502+000), which receives water from the Indus River. It is located between 30.9634º N and 70.9394º E and is about 150m from the Mean Sea Level (MSL). The topography of the area irrigated by the Munda Branch is predominantly flat and has a semi-arid climate. The district experiences an average rainfall of 200-300mm, with maximum precipitation from July to September in the monsoon season.

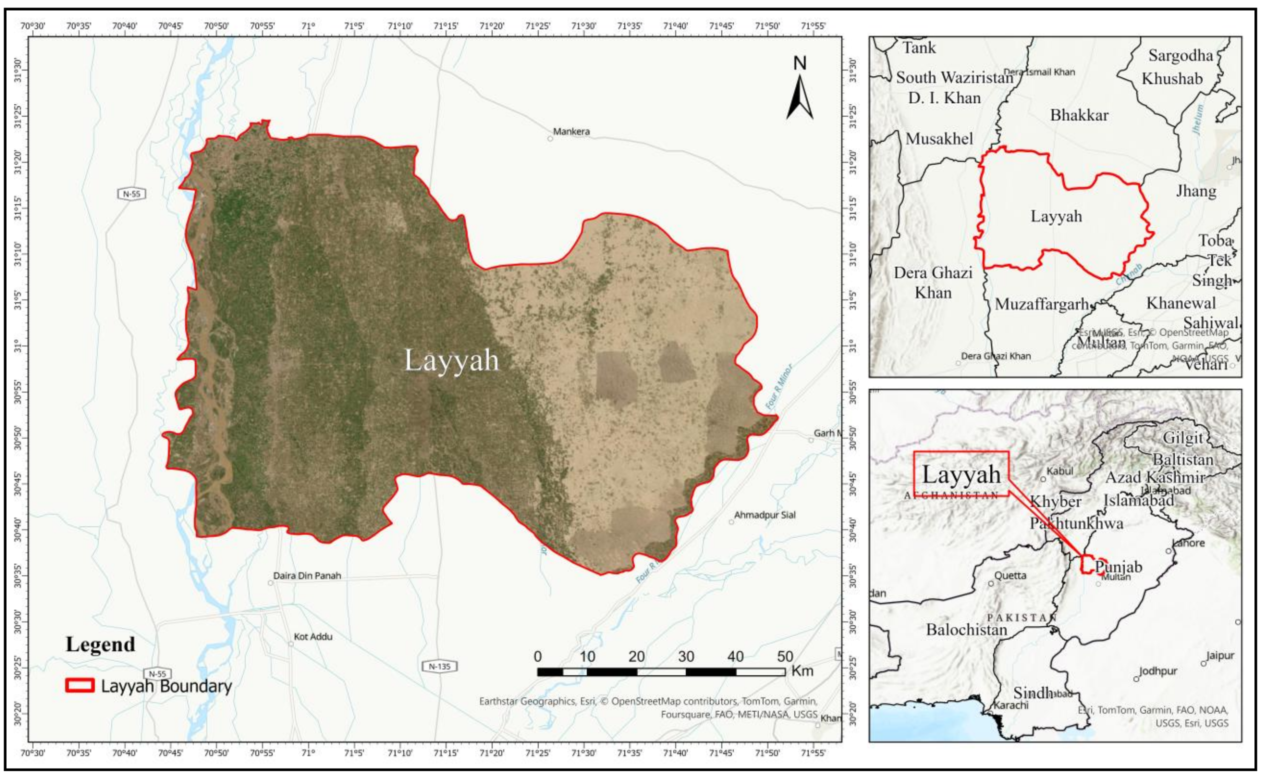


Fig 3.1. Map of Layyah Division

The Munda Branch is 34 km long and has a designed discharge capacity of 39.5 m^3/s. The Munda Branch Canal has 9 distributaries which distribute water from the branch canal to the farmlands. The details of all the distributaries emerging from the Munda Branch with their design discharge are provided in **Fig 3.4.** Field observation has been taken at RD (1+000) head, RD (112+000) and tail of the Munda Branch Canal.

The soils of the region are fertile, with ranges from sandy loam to clay loam, providing excellent features for the growth of crops like rice, cotton, wheat, sugarcane, and maize. The hydrology of the Munda Branch has been heavily influenced with respect to variation in the Main Line Lower Canal, and efficient water management practices are critically important to optimize and distribute water.

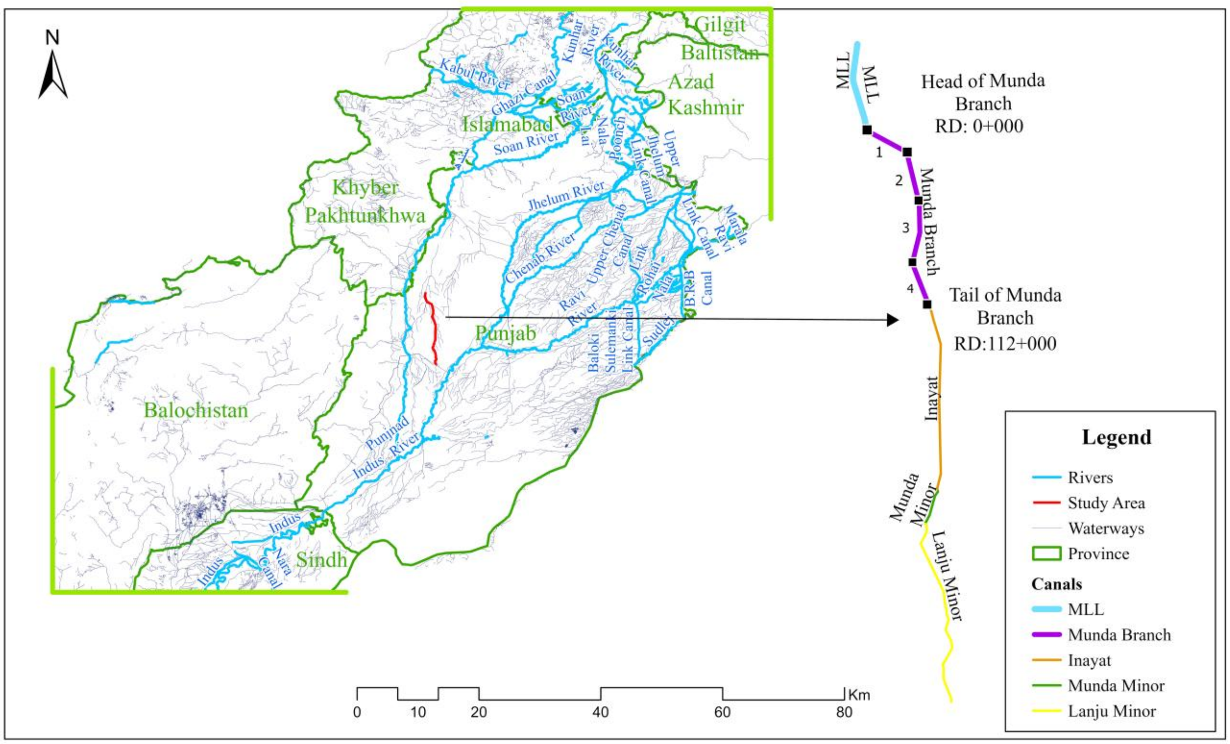


Fig 3.2. Study area map of the Munda Branch Canal

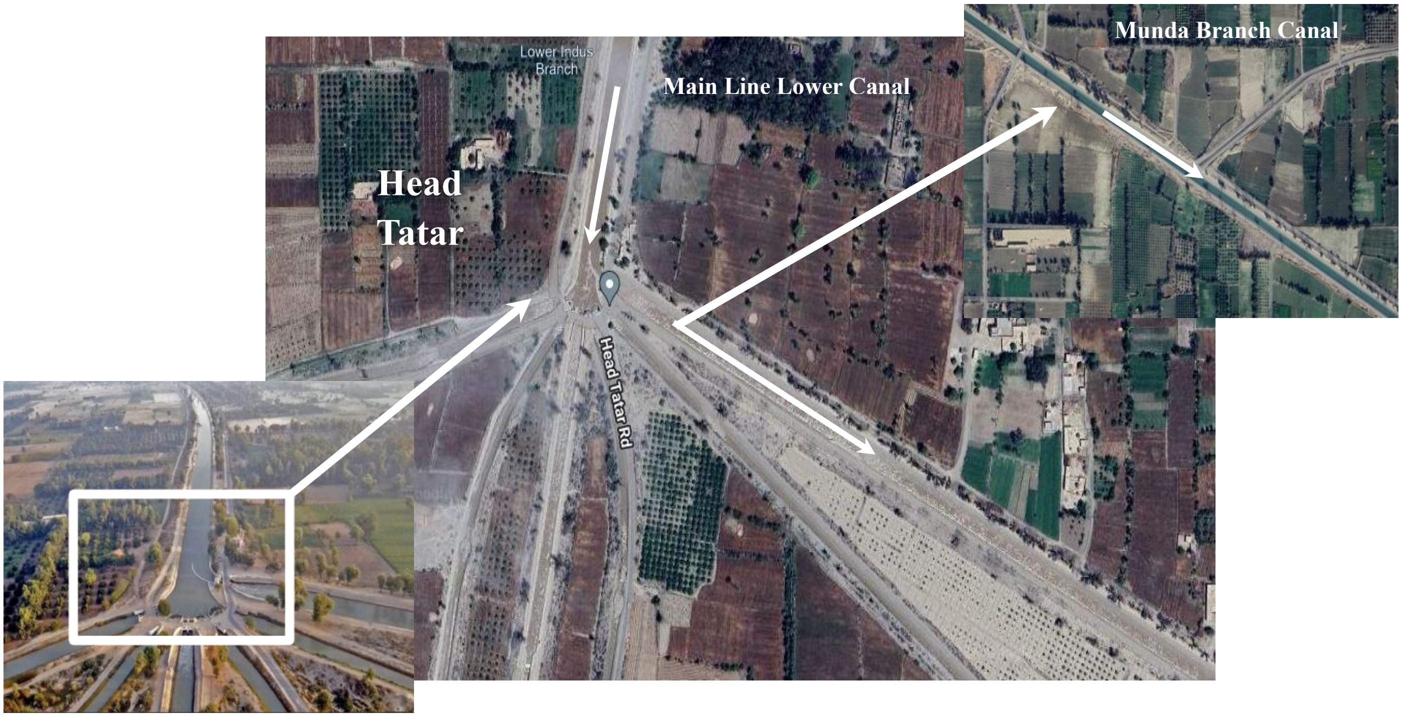
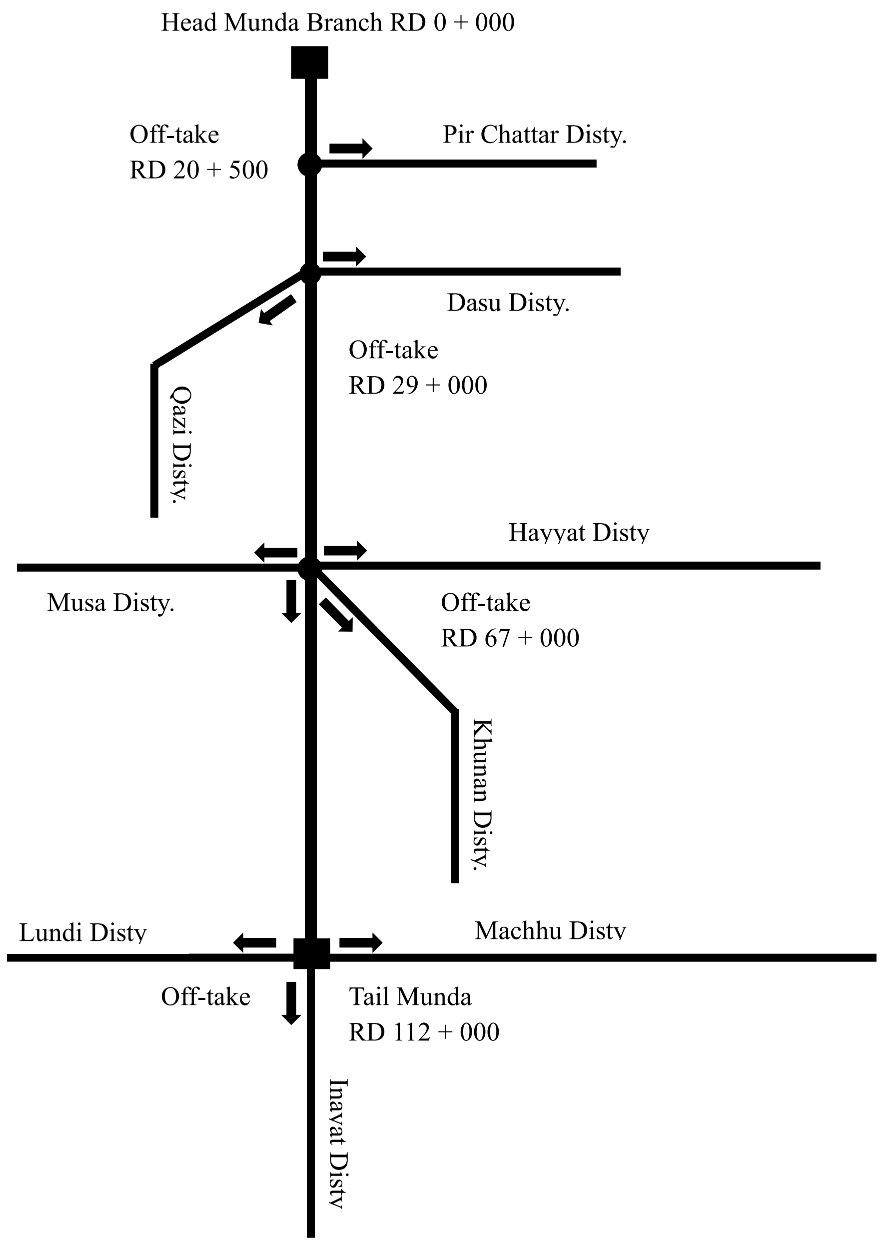


Fig 3.3. Main canal and branch canal in the study area.



Total Discharges at different takeoffs (m³/s)	**39.53**
Pir Chattar Disty	0.155
Dasu Disty	4.578
Qazi Disty	0.498
Hayyat Disty	15.10
Musa Disty	1.697
Khunan Disty	0.777
Machuu Disty	4.765
Lundi Disty	0.903
Inayat Disty	9.919
Total lateral takeoff Discharge	38.39

Discharge Summary (m³/s)	
Head Discharge	39.53
Total lateral Discharge	38.39
Designed outlet discharge	0.045
Losses as per L section	1.092

Fig 3.4. Line diagram of the Munda Branch Canal and distributaries with summary of designed discharges

3.2. Data

For precise and accurate hydrodynamic analysis, modeling in HEC-RAS depends on the data set, including the cross-section and geometry of the channels. The discharge-to-head relationship is used to measure the flow rates at the head and tail of the canals and distributaries. The Layyah Canal Division utilizes these stream-gauging techniques, which have been developed by the PMIU (Program Monitoring and Implementation Unit). For hydrological studies and investigation of the canal regimes, the PMIU uses the current meter. PID Layyah consults PMIU for field surveys and observations whenever a variation is observed in the channels. Afterward, discharge tables are prepared for the rabi and kharif crop seasons.

Guage	**0.30**	**0.02**	**0.03**	**0.05**	**0.06**	**0.08**	**0.09**
0.00	0.00	0.03	0.08	0.14	0.23	0.31	0.42
0.30	2.58	2.29	2.97	3.17	3.37	3.59	3.82
0.61	7.27	7.56	7.84	8.12	8.41	8.69	8.97
0.91	13.36	13.70	14.04	14.38	14.72	15.08	15.42
1.22	20.01	20.97	21.37	21.73	22.13	22.53	22.95
1.52	28.75	29.21	29.63	30.05	30.51	31.07	31.38
1.83	37.81	38.29	39.22	39.70	39.70	40.19	40.67

Table 3.1. Discharge table (DT) for the head of the Munda Branch Canal

The PID then implements these discharge tables for the particular season. In order to measure the discharge staff reader notes the corresponding (water depth) on the staff gauges installed at the head and tail of the channels and consults with the DT readings. A detail of the DT table for the head of the Munda Branch Canal prepared by the PMIU is described in **Table 3.1.** In this research analysis, 4 months of flow data have been used for different seasons based on water availability. For modeling the Munda Branch in HEC-RAS, the data required is shown in **Table 3.2.** The geometric data for defining the geometry of the channels has been derived from the design table described in **Table 3.3.**

Table 3.2. Description of the data and data source

Type of data	Data source	Data granularity
L-section details	PID Layyah	Fixed data
Head regulators details	PID Layyah	Fixed data
Cross regulators details	PID Layyah	Fixed data
Lateral outlets details	PID Layyah	Fixed data
Flow hydrographs	PID Layyah	Daily data

The Munda Branch has been divided into four different reaches based on bed level, water surface slope, channel bed, velocity, discharge, full supply level, Manning's n value, and full supply depth. The geometric file has been generated from the data collected at different RD along the Munda Branch. It allows the HEC-RAS model to simulate both the steady and unsteady flow changes.

Table 3.3. Detail of L-section data used for developing the geometry of Munda Branch Canal

Reach No	Reach RD	Bed Level (msl.m)	F.S Depth (m)	Velocity (m/s)	F.S Discharge (m3/s)	Value of Lacye's f	Value of 'n'	Slope (m/m)
1	20500	154.66	4.04	1.18	39.53	1.57	0.017	0.016
2	29000	152.99	3.99	1.18	35.28	1.57	0.017	0.016
3	67000	149.97	3.62	1.23	34.00	1.83	0.017	0.002
4	112000	147.32	2.89	1.01	17.81	1.53	0.017	0.00018

All four reaches of the Munda Branch have been uniformly distributed at about 154m (500ft) intervals along the channel. The data for these sections was collected from the U/D head of the Munda Branch (RD 0+000) to the D/S tail (RD 112+000). A description of the cross-section plot for the Munda Branch and detail of the cross-sections within each reach of canal are shown in **Fig 3.5** and **Table 3.4** respectively.

Table 3.4. Reach length and number of cross section developed in HEC-RAS

Reach No.	Reach RD	Distance modelled (km)	No of cross-sections developed
Reach 1	20500	6.248	41
Reach 2	29000	2.591	17
Reach 3	67000	11.582	76
Reach 4	112000	13.716	90

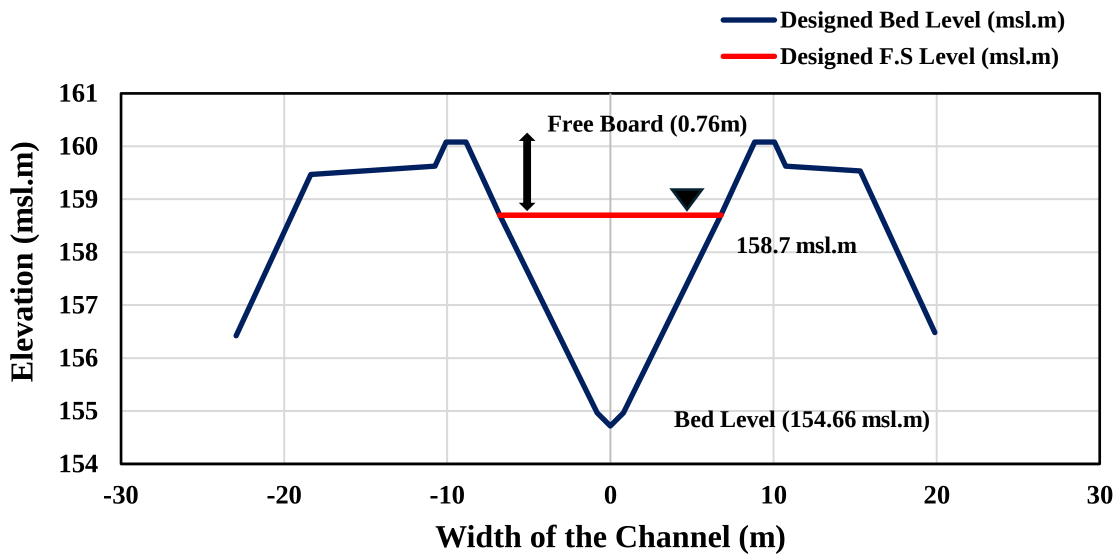


Fig 3.5. A typical cross section of Munda Branch Canal

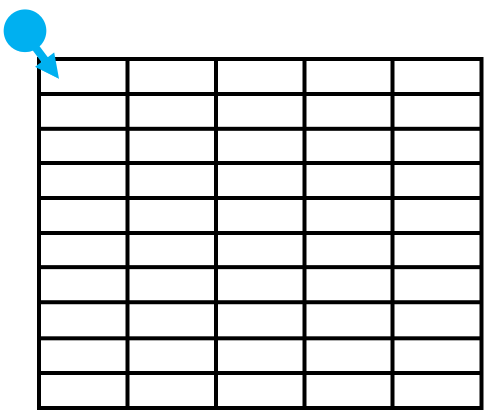
3.3. Overview of the Warabandi (Rotational System)

Layyah Canal Division, like other traditional irrigation systems, uses rotational irrigation methods (warabandi), primarily designed to distribute water from a common source to farmers with different irrigated areas and according to their fair share. The basic principle of the system is to provide equitable water distribution from one farmer to the other within one block and then to another block. It forms a system based on a fixed rotational schedule, with each farmer receiving water on a fixed day of the week.

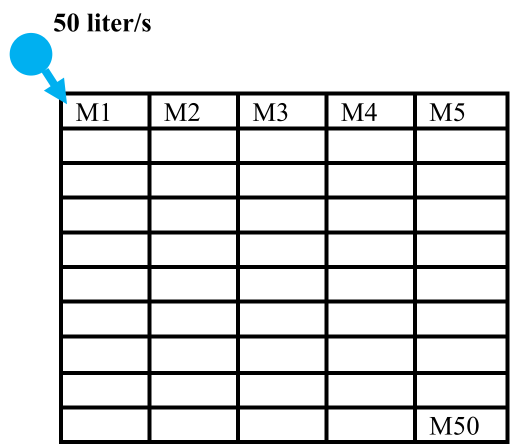
The mode of distribution leads to the setting of the canal capacity in which the size of the canal is set to the module within one block. The U/S upstream of the block is adjusted for the constant discharge based on the required irrigated area. Based on the irrigation techniques used in the field, the module contains discharge capacities from (0.03-0.1) m^3/s and does not account for the size of the command area or need of the crop (Fao, 2008).

The water requirement is balanced by adjusting the duration of the turn and the farmer's participation, adhering to the schedule. The size of the block is designed according to peak discharge resulting from the ability of the module to operate under peak flow. The block is so devised that the cycle restarts from the first user after irrigating the last one. To ensure fair water distribution and allocation, the schedule/irrigation period is structured to guarantee that the day and night irrigation times are equally shared among the farmers.

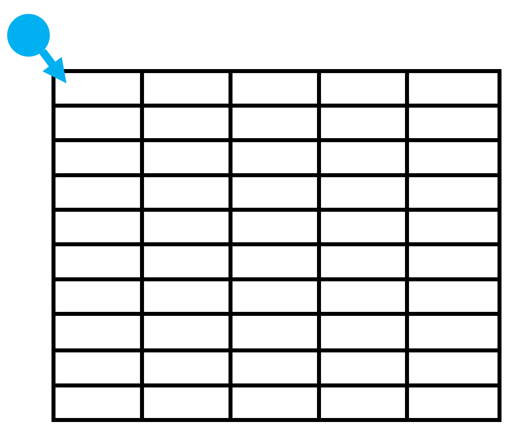
For example, the schedule could be based on a week and 8-hour cycle. With this rotation period, a user who starts irrigation at 10:00 on Friday will begin at 18:00 next Friday. **Fig 3.6** illustrates the rotation of water within the block of 50 hectares area in Layyah in which the water needed at peak is 1 liter/s/ha and module of 50 liter/s ($0.05 m^3/s$) will be distributed within the block.



Block 1



Block 2



Block 3

Fig 3.6. A description of typical organization rotational system per block for 50 hectares area in Layyah. (The module in the rotational system rotates from M1 to M2 and ….. terminates at the M50 and starts from M1 again).

3.4. Canal operation methods and regulatory framerwork

The system of canal division in PID Layyah is based on sluice gates. The method of operating the canal consists of manipulating the gates and structure manually to ensure fair water distribution according to a weekly schedule. Warm-up gears are used to raise or lower the gates. Gates are provided with high torque low RPM machines, operated by the gauge reader and regulation staff appointed on the head of the Munda Branch. The manipulation of the gates is based on a discharge control system. The process involves controlling the discharge of lateral/inline structures of intermediate channels or distributaries. The DIC (discharge control) is developed to maintain a fixed flow rate at D/S downstream, which involves the closure of the gates at slower rates until the discharge is stabilized in the Munda Branch Canal. With this system, a perfect delivery hydrograph at the D/S is achieved, but several interventions are required during the period of instability and fluctuations.

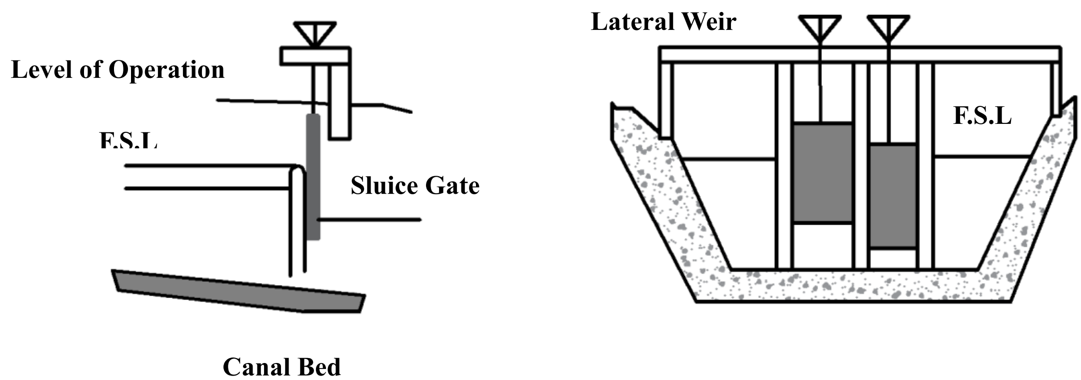


Fig 3.7. A cross section of the cross regulator with operation gates in the Munda Branch

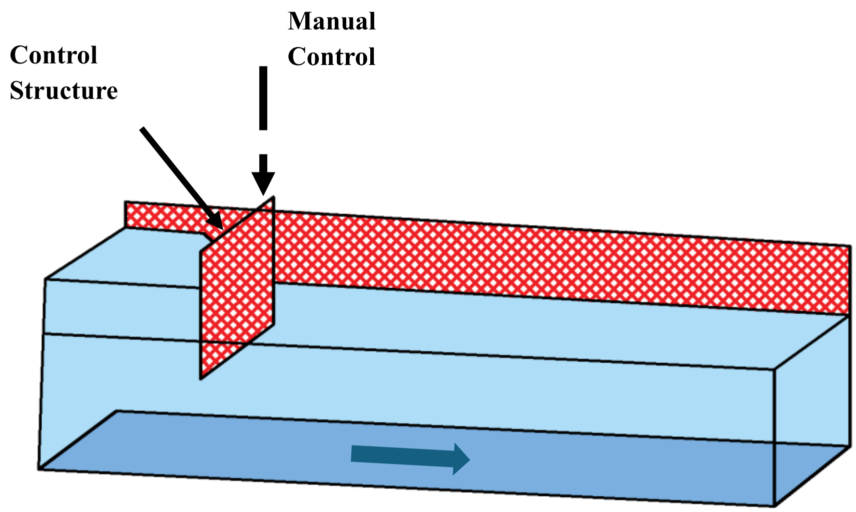


Fig 3.8. A description of typical manual control gated system in canals

The PID Layyah develops and implements a weekly rotational program to compensate for the water scarcity issue. A regular weekly schedule for the whole season is issued by the Superintending Engineer and implemented by the regulation in-charge.This program divides the distributaries into three groups and six subgroups with preference order. According to this fixed schedule, the 1st group will preferably be supplied first; the remaining water will be given to group 2nd and similarly to 3rd group. A description of the weekly rotational program 2023-24 for the Layyah Canal Division is provided in the appendix.

3.5. Description of HEC-RAS Model

A daily discharge model for the Munda Branch Canal was developed in HEC-RAS, and the simulated results were compared with DT gathered by PMIU. Afterward, calibration and validation of the HEC-RAS model were done by using seasonal data at U/S (Head) and D/S (Tail) of the

Munda Branch for water elevations and flow rates, respectively. **Fig 3.9** describes the methodology and approach to develop the HEC-RAS model for the Munda Branch Canal.

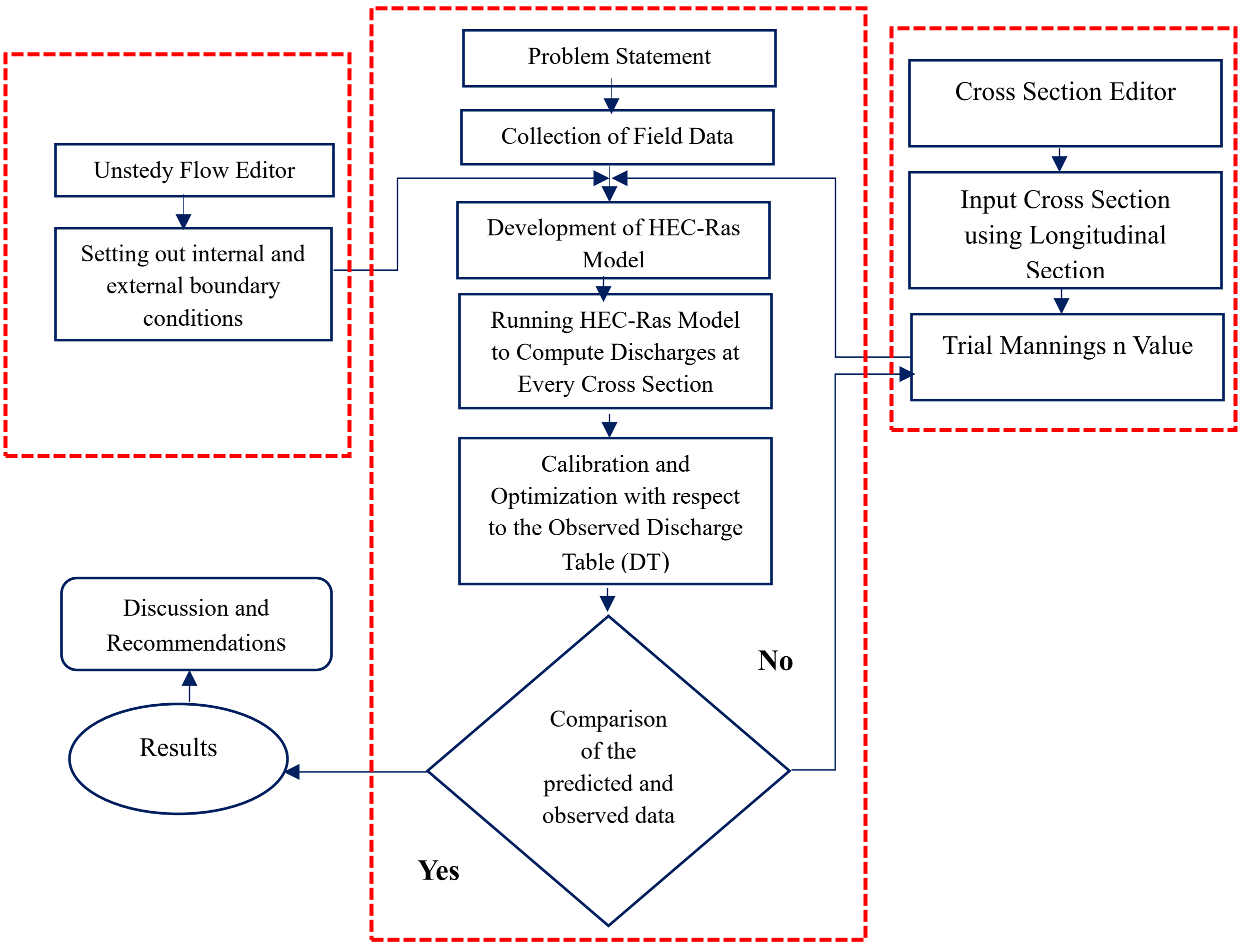


Fig 3.9. Flow chart of the methodology used for the HEC-RAS model developed

HEC-RAS is a one-dimensional model created by the Hydrologic Engineering Centre of the U.S. Army Corps of Engineering. The 1D model is commonly used to analyze the dynamics of river systems and artificial channels. Development of the model in HEC-RAS involves the creation of the geometry either by DEM (digital elevation model) or by defining the central line and bank line of the canal in RAS Mapper (HEC-RAS River Analysis System Hydraulic Reference Manual, 2016). The depiction of the cross-section plot generated in HEC-RAS at the head of the Munda Branch Canal RD (1+000) is shown in **Fig 3.10** and **3.11.** The cross sections are evenly distributed at 154m and depend on the reach-specific features such as channel bad slope, bed elevation, and water depth.

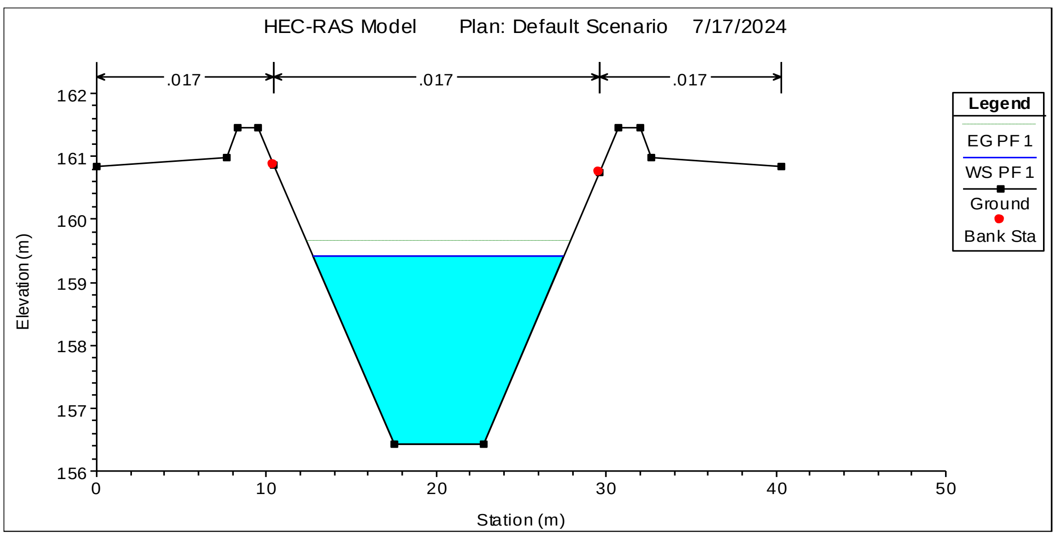


Fig 3.10. A cross section of the Main Line Lower Canal developed in HEC-RAS

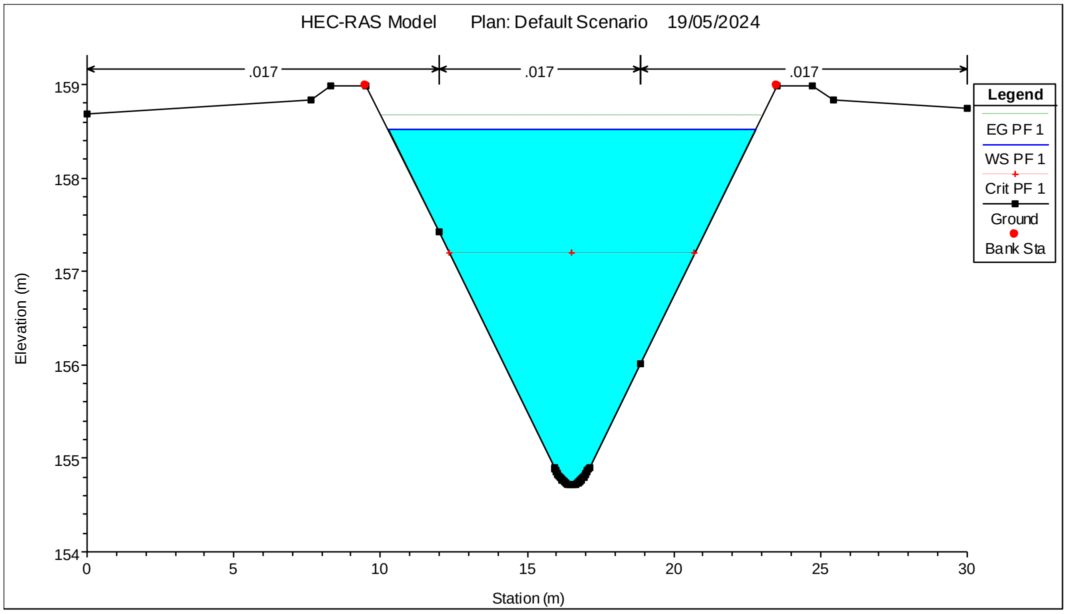


Fig 3.11. A cross section of the Munda Branch Canal developed in HEC-RAS

HEC-RAS uses fundamental equations dealing with the discharges in the open channels, such as continuity and momentum equations. It can easily model any inline and lateral hydraulic structures (gated spillways, weirs, and outlets). The continuity equation represents the conservation of mass in hydraulic systems. Similarly, the momentum equation involves the conservation of momentum depending on various key factors, such as discharge, area, water depth, and frictional slope.

HEC-RAS uses the Saint-Venant equations to simulate the water surface profiles and solve the equation numerically under different discharge conditions and scenarios. The model could be employed for both the steady and unsteady state simulations. In this research, an unsteady state simulation model was developed, which involves variation in the flow condition with time and distance. The model is suitable for studies involving flood risk management and operational changes in canal geometry and varying boundary conditions.For analyzing the dynamics of the irrigation canal network, HEC-RAS utilizes Saint-Venant equations, which define the conservation of momentum and mass in the channels.

The continuity equation represents the law of conservation of mass and is represented as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

Where:

A= cross-sectional area of flow (m^3/s), Q= Discharge (flow rate in m3/s), t= time (sec),

x= Distance along the canal (m)

The momentum equation describes the law of conservation of momentum incorporating forces such as inertial, pressure, and gravity. The momentum equation is described as:

$$\frac{\partial Q}{\partial t} + \frac{\partial (\frac{Q^2}{A})}{\partial x} + gA\frac{\partial h}{\partial x} + gA(S_o - S_f) = 0$$

Where:

A= cross-sectional area of flow (m^3/s), Q= Discharge (flow rate in m^3/s), t= time (sec),

x= Distance along the canal (m), g= acceleration due to gravity (9.81m/s^2), S_o= Bed slope of the channel (m/m), S_f= Frictional slope, h= Water surface elevation (m).

HEC-RAS combines both equations to simulate water surface elevations and discharges for both steady and unsteady flow conditions, making it pivotal for the hydrodynamic analysis of irrigation canals.

3.6. Inline and Lateral Structures in HEC-RAS

HEC-RAS provides multiple options to model gated spillways and weirs for adding inline structures in canal channels. It provides a combination of options with overflow gates, radial gates, and vertical lift gates often used as sluice gates. In this study, the inline and lateral structures consist of vertical gates (sluice) for managing the flows in the distributaries and minor canals. HEC-RAS has the ability to do numerical calculations for both the submerged and free flow through the openings of gates. **Table 3.5** provides details of all types of inline and lateral structures with all the design details.

Table 3.5. Summary of the inline and lateral structure

No	Channel Name	Type of Canal Structure	Gated/ Ungated	No of Gates	Height of Gate (m)	Width of Gate (m)	Working Head (m)	Bed Level (m)	F.S Level (m)	Crest Level (m)	F.S Depth (m)
1	Pir Chattar Disty	Cross Regulator	Gated	1	1.16	0.82	0.2	156.8	156.9	156.8	0.1
2	Dasu Disty	Cross Regulator	Gated	2	1.16	2.77	1.8	156.9	157.8	156.8	1.0
3	Qazi Disty	Cross Regulator	Gated	1	1.16	1.23	1.1	157.7	158.2	157.5	0.5
4	Hayyat Disty	Cross Regulator	Gated	3	1.13	2.77	2.2	153.2	154.6	153.0	1.4
5	Musa Disty	Cross Regulator	Gated	1	1.13	2.77	0.8	153.9	156.9	154.4	0.7
6	Khunan Disty	Cross Regulator	Gated	1	1.16	1.85	0.7	153.9	157.7	154.6	0.6
7	Machuu Disty	Cross Regulator	Gated	2	1.16	1.93	2.4	150.4	151.2	150.8	0.9
8	Lundi Disty	Cross Regulator	Gated	1	1.16	0.82	2.4	150.6	151.2	150.8	0.6
9	Inayat Disty	Cross Regulator	Gated	3	1.13	2.77	2.3	150.1	151.3	150.8	1.2
10	Munda Branch	Outlet		-	-			-	-	-	-

The standard weir equation used in HEC-RAS for calculation flow through weirs is given as:

$$Q = CLH^{\frac{3}{2}}$$

Where: Q= flow rate (m^3/s), C= weir flow coefficient, L= weir length (m), H= weir energy head (m). Moreover, for the gated inline and weirs, the gate openings were adjusted to maintain the Full Supply Level (FSL), considering the difference in the discharge head through the gate. The orifice discharge equation is described as:

$$Q = C_d A\sqrt{2g\ (H_u - H_d)}$$

Fig 3.12. A depiction of the gated inline structure at the Munda Branch Canal during second observation

Q = discharge (m^3/s), C_d= discharge coefficient, A= area of the gate opening, g= acceleration due to gravity (m/s2), H_u= upstream head (m), H_d= downstream head (m). The description of a gated spillway in terms of inline structure is shown in **Fig 3.12** and **3.13.**

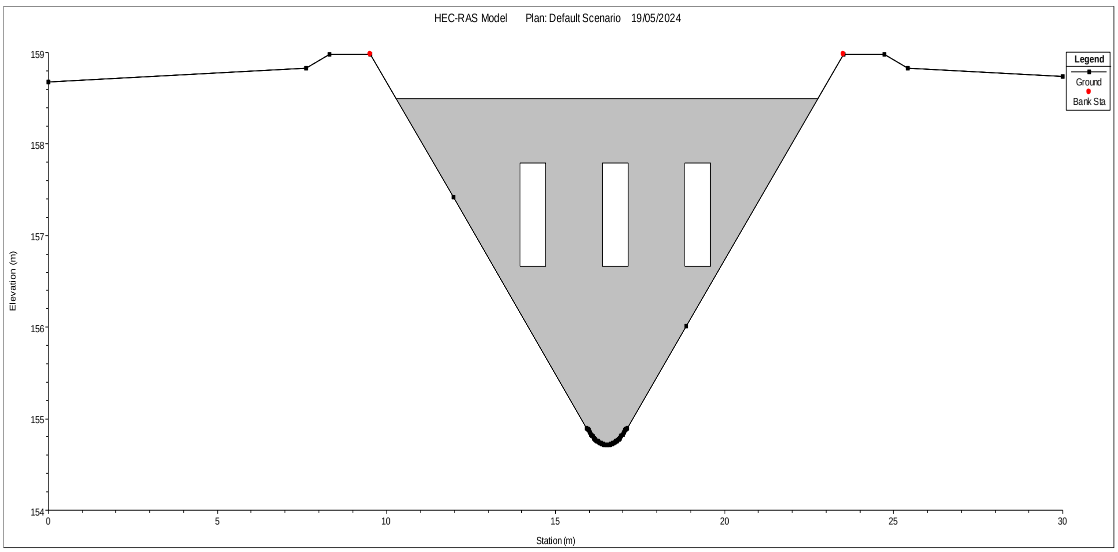


Fig 3.13. A cross section of inline structure at Munda Branch developed in HEC-RAS

3.7. Boundary Conditions in HEC-RAS Model

To perform hydrodynamic analysis with both steady and unsteady flow conditions, HEC-RAS requires cross-sectional data in the form of a geometric file and discharge data file with U/S and D/S conditions. In this study, an unsteady state simulation has been done with mixed flow regime conditions. For the hydrodynamic modeling, HEC-RAS utilizes two types of boundary conditions (upstream and downstream) with either steady or unsteady flow conditions. In irrigation canals, the flow is normally subcritical, managed by setting downstream conditions such as normal depth, as in the case of the Munda Branch Canal. The upstream boundary condition demands the flow data, which has been provided in the form of daily discharge data obtained from DT. Downstream boundary conditions restrict the discharge at the tail end of the canal or downstream.

The model provides multiple options to set downstream boundary conditions, such as rating curves, normal depth, and stage hydrographs. The model in this study uses normal depth as a downstream boundary condition for the unsteady flow analysis. In an unsteady state simulation, the water depth changes along the canal's reach with respect to time. Moreover, considering the hydraulic impact of structures like weirs and spillways, the model requires internal boundary conditions. The inline and lateral structures in the Munda Branch are provided with internal boundary conditions depending on the water levels in the parent canal and gate openings. The description of the boundary conditions used by the HEC-RAS has been provided in **Table 3.6.**

Table 3.6. Description of the boundary conditions used in HEC-RAS

Type of Hydraulic Structures	Internal boundary conditions	External boundary conditions
Flow hydrograph	-	U/S boundary condition (Head)
Normal depth	-	D/S boundary condition (Tail)
Gated outlets	Gate openings time series	Internal boundary condition
Cross/head regulators	Elevation-controlled gates	Internal boundary condition
Canal falls (gated)	Elevation-controlled gates	Internal boundary condition
Gated distributaries	Rule based	-

CHAPTER 4

4 RESULTS AND DISCUSSION

A hydrodynamic model for the Munda Branch was developed in HEC-RAS and BASEMENT to evaluate the performance of the canal. Following the development of the model, it was calculated by adjusting key parameters to ensure that it maintains the Full Supply Level (F.S.L) as designated to all the four reaches of the Munda Branch. Internal and external boundary conditions were allocated for the calibration process. A comprehensive analysis of the results obtained from HEC-RAS and BASEMENT was done for the Munda Branch Canal. By comparing both models, the hydraulic performance of the Munda was identified for their possible implications in the canal operation. The model was developed in HEC-RAS based on design discharges allocated to The Munda Branch and its distributaries at different RD. Later, the model was calibrated by achieving Manning's n value of 0.017 and comparing it with the designed flow rates of each reach in the Munda Branch obtained from the L-Section data.

4.1. Evaluating observed water levels without any structure

During the first scenario, the Munda Branch was modeled to evaluate the baseline behavior without any lateral structure for the distributaries and inline structures. **Fig 4.1** plots a graph between bed levels, bank levels, and simulated water surface profile from the BASEMENT model. The figure shows that water surface elevation for various cross sections at the Munda Branch surpasses the bed and bank levels. It could be observed from the graph that the canal is prone to submergence as the banks overflow at several RD/cross sections.

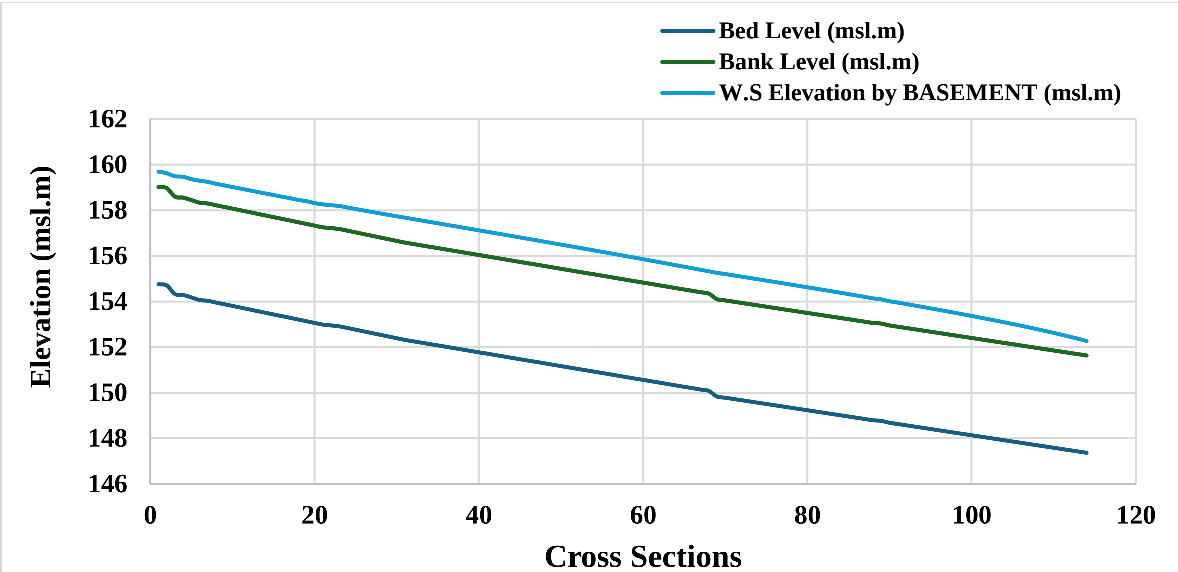


Fig 4.1. Comparison of the bed levels, bank levels, and water elevation by BASEMENT

Similarly, **Fig 4.2** illustrates a plot between the water surface profile and bed levels of the canal modeled in HEC-RAS. It is indicated that water levels are consistently above the bed levels of the Munda Branch, which shows significant submergence. **Fig 4.1** and **4.2**, the analysis provides similar behavior regarding the submergence of the canal.

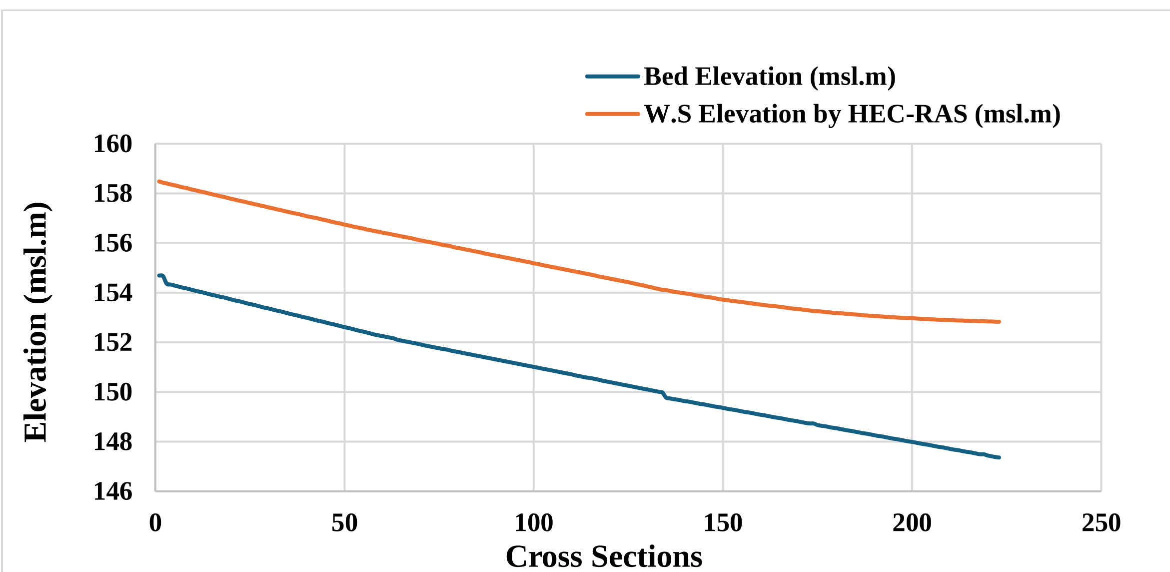


Fig 4.2. Comparison of the bed levels, and water elevation by HEC-RAS

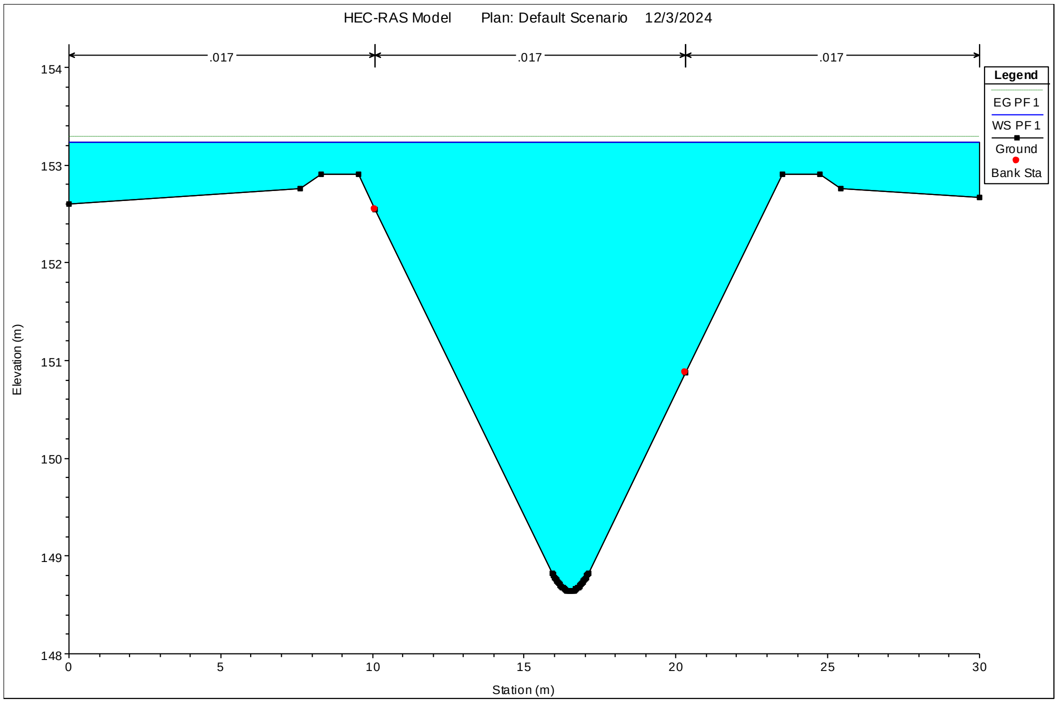


Fig 4.3. Cross section at RD 20+500 near the U/S of the Munda Branch in HEC-RAS

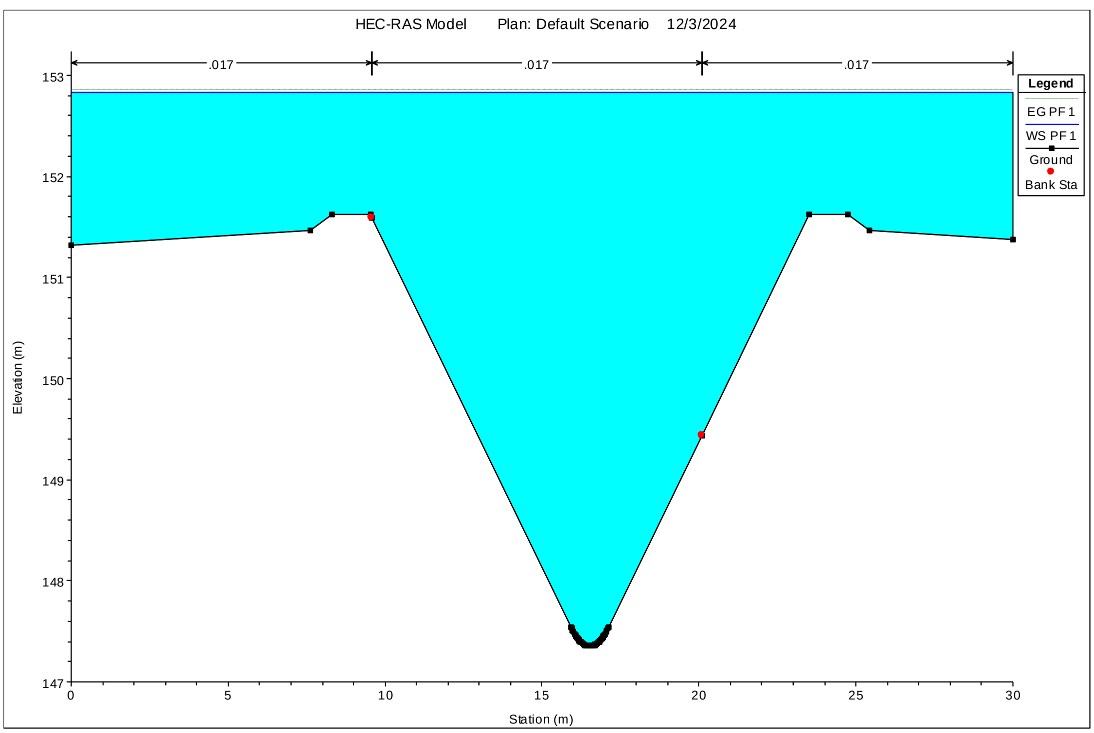


Fig 4.4. Cross section at RD 112+000 near the D/S of the Munda Branch Canal in HEC-RAS

Figures 4.3 and **4.4** show a plot of the cross-section at the U/S and D/S of the Munda Branch, respectively. The plots of various cross-sections in HEC-RAS show significant submergence of the banks of Munda as the water surface profile exceeds the bank level at the respective cross-section.

4.2. Analysis of the water surface profile with lateral structures

In the second scenario with the lateral offtakes, the lateral distributaries were incorporated into the canal system to draw the design discharge from the lateral offtakes. The lateral distributaries of the Munda Branch Canal are equipped with gated structures, which provide the boundary conditions for the HEC-RAS model. The boundary conditions for the lateral distributaries depend on the head (depth) of the water, and the gates are operated accordingly to maintain the water depth in the subsequent distributary. For the simulation in the HEC-RAS and BASEMENT, the lateral distributaries were assigned corresponding design discharges. The HEC-RAS model utilizes design discharge data as a U/S boundary condition and fixed water depth at the D/S of the Munda Branch Canal.

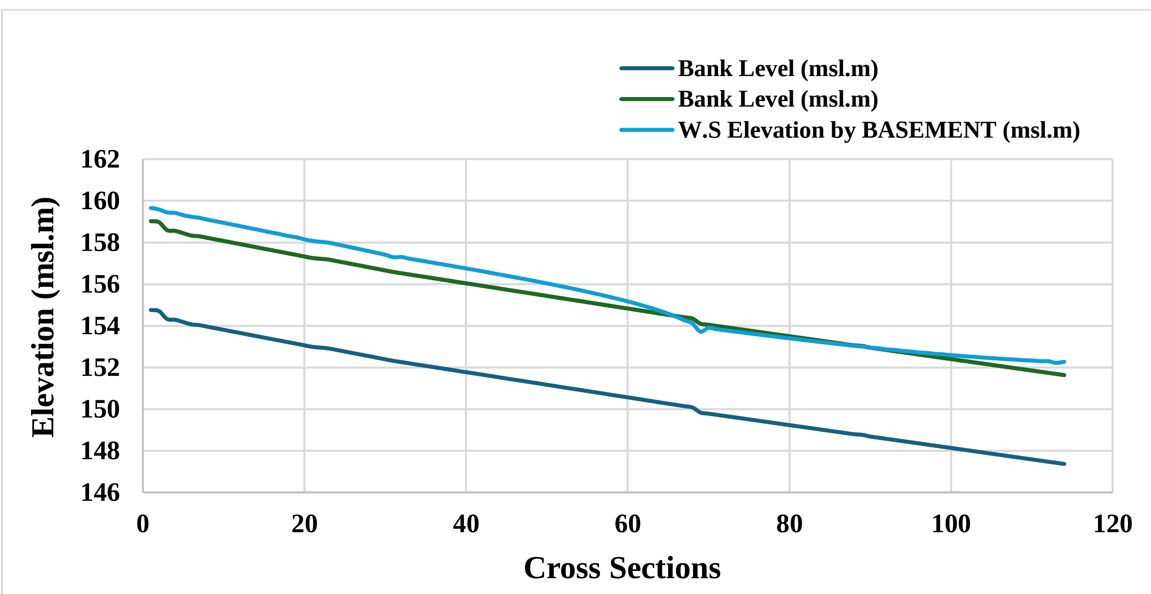


Fig 4.5. Water surface elevation of the Munda Branch with Q laterals in BASEMENT

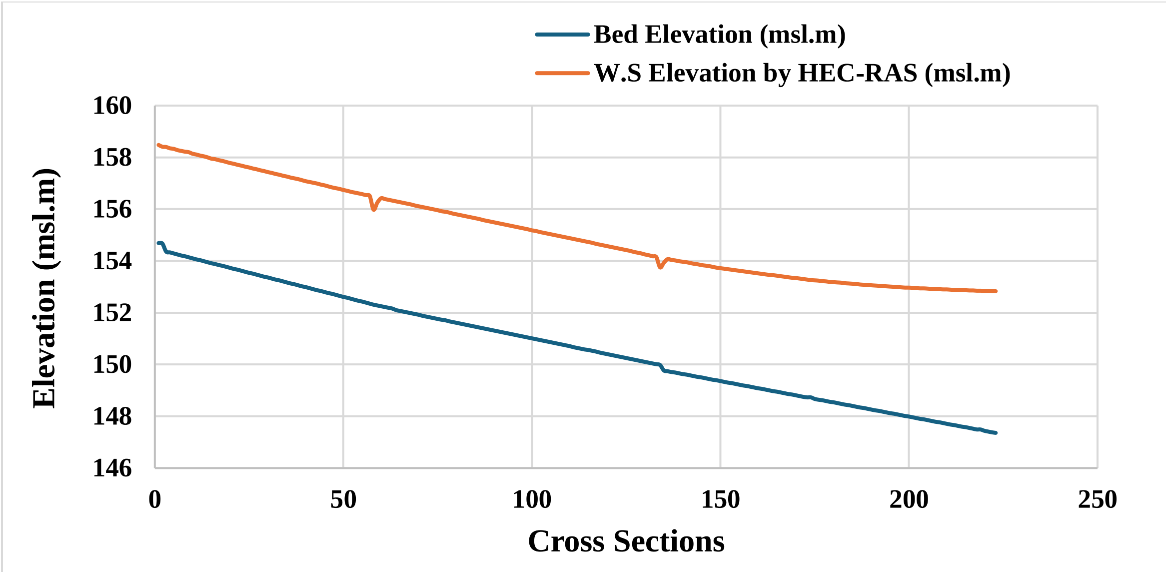


Fig 4.6. Water levels at different RD of the Munda Branch with lateral offtakes in HEC-RAS

Fig 4.5 depicts a plot between the water surface elevation of the Munda Branch at various cross-sections versus bank levels in the BASEMENT model. It is noted that while the lateral offtakes are drawing their designed discharges and reducing the flow in the central canal, the water levels exceed the bank levels in the Munda. Moreover, it is observed that more than the partial relief provided by the lateral offtakes is needed and needs to be improved regarding the capacity of the Munda Branch.

Figure 4.6 illustrates a graphical representation of bed levels and water surface elevations of the Munda Branch at various cross sections in HEC-RAS model. The results from the HEC-RAS model show some discrepancies at the RD 29000 and RD 67000 as discharges were taken off from the lateral distributaries but the overall pattern for both the models remains same for both the models.

4.3. Analysis of the water levels with inline and lateral structures

In the third scenario, both models incorporate inline structures, such as gated weirs within the Munda Branch Canal. HEC-RAS provides multiple options to model gated spillways and weirs for adding inline structures in canal channels. It provides a combination of options with overflow gates, radial gates, and vertical lift gates often used as sluice gates. In this study, the inline and lateral structures consist of vertical gates (sluice) for managing the flows in the distributaries and minor canals.

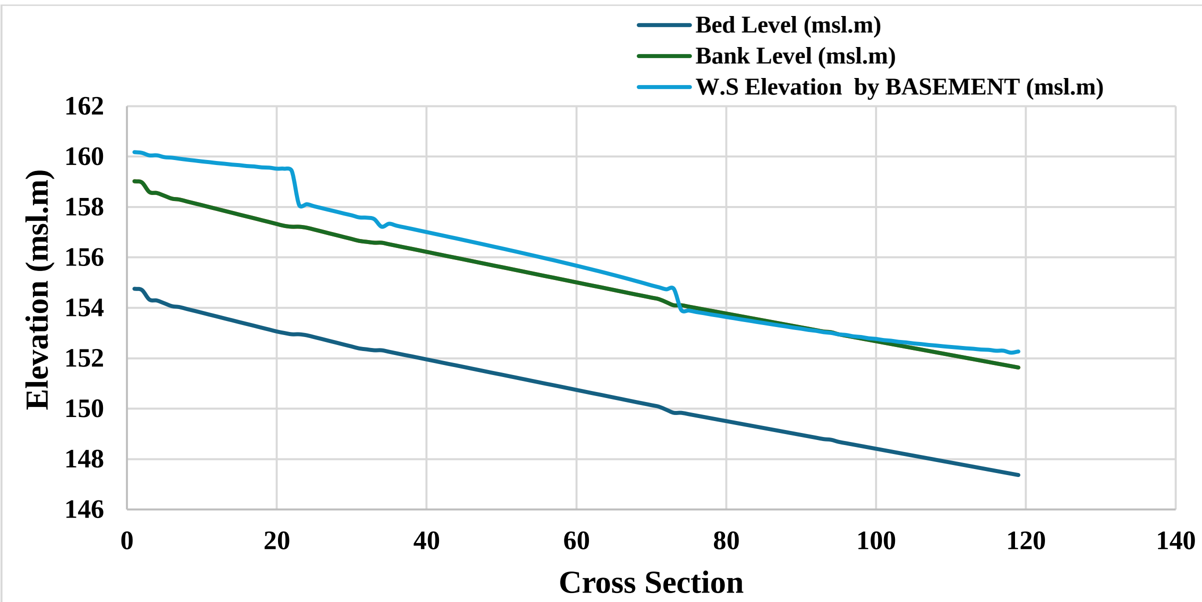


Fig 4.7. Water surface elevation of the Munda Branch with inline structure in BASEMENT

HEC-RAS can do numerical calculations for both the submerged and free flow through the openings of gates. The BASEMENT model indicates that the inline structure caused localized variation in the water levels of the Munda Branch. **Fig 4.7** explains the graphical comparison between the bank levels and water surface elevation at different cross sections of the branch canal. By incorporating inline structures in the Munda, the water levels remain above the bank levels in critical sections.

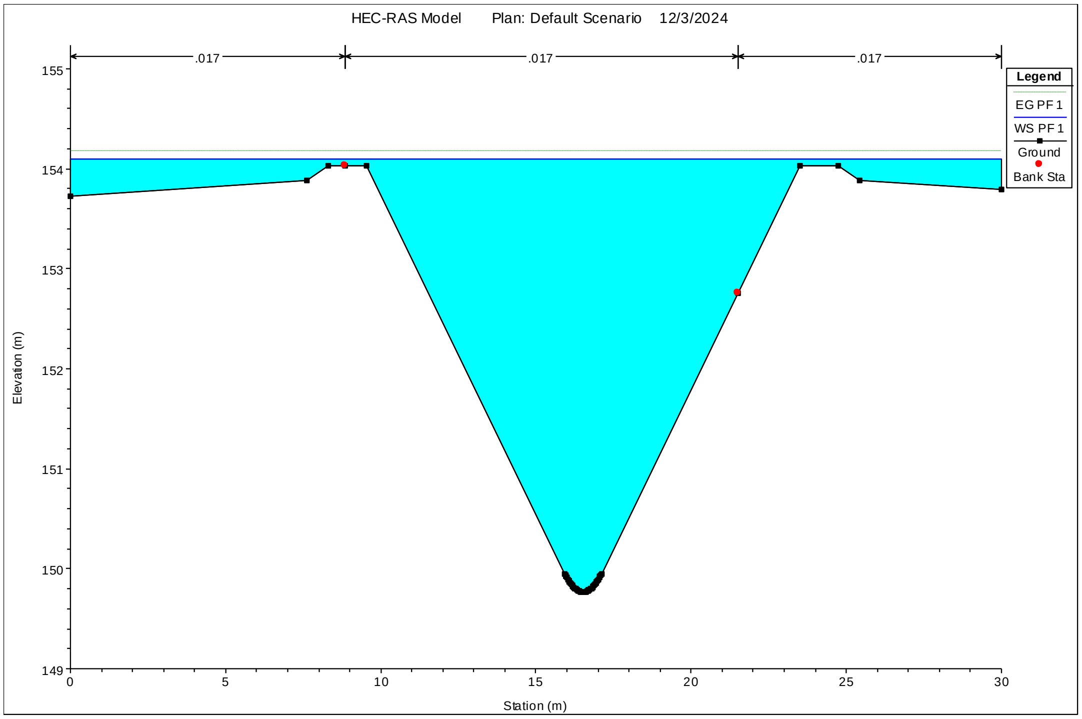


Fig 4.8. Cross section at the U/S of the Munda with lateral and inline structure in HEC-RAS

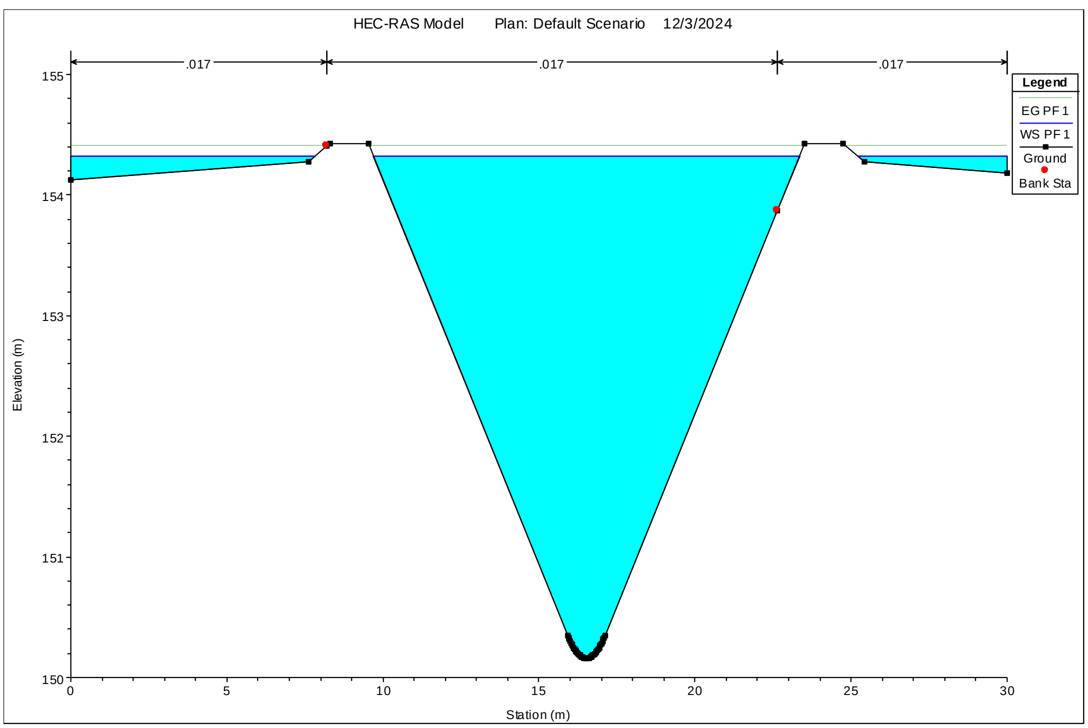


Fig 4.9. Cross section at the D/S of the Munda with lateral and inline structure in HEC-RAS

Figure 4.8 and **4.9** shows cross sections of the Munda Branch developed in HEC-RAS. The figures demonstrate that even though the canal was equipped with the lateral offtakes and inline structures most of the sections along the canal indicate that existing canal geometry is insufficient to accommodate the design discharges of the lateral distributaries without causing the submergence of the banks of the Munda.

CHAPTER 5

5 CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The HEC-RAS and BASEMENT model for the Munda Branch and its distributaries were developed for hydrodynamic analysis. The research focused on the investigation and development of the 1D hydrodynamic model for the Munda Branch Canal for evaluating the water surface profile at various cross sections of the Munda. The canal's water levels were examined under three scenarios: 1. without any hydraulic structures, 2. the incorporation of the lateral offtakes, and 3. the enactment of the inline structures.

Both the HEC-RAS and BASEMENT models provided consistent water surface profiles. However, minor discrepancies were explicitly found at RD 29000 RD 67000. Still, most cross-sections followed the same pattern in both models, confirming the validity of both tools in the hydrodynamic analysis of the irrigation schemes. The outcomes displayed that most of Munda's cross-section remained submerged under the designed flow rates, even with the implementation of the lateral offtakes and inline structures. This emphasizes the limiting capacity of the Munda with the design discharges and additional flows without the risk of submergence/overtopping or structural failure.

The addition of the inline and lateral structures caused localized variation in the water surface profiles at particular cross sections, highlighting these structures' careful calibration and operation. The comparative analysis of both the software HEC-RAS and BASEMENT proved effective for the canal network simulation.

5.2. Recommendations

The following recommendations are suggested to increase the sustainability of the irrigation canal system.

1. Due to the limited capability of the Munda Branch Canal, it is recommended to improve the embankments and increase cross-sectional areas to counter higher discharges.
2. Inline and lateral structures are very crucial regarding water distribution, so it is imperative to maintain regular inspection of such hydraulic structures.

3. The system of the irrigation canal network in Layyah is based on sluice gates, operated manually. Due to continuous use of the gates there is also a risk of premature deterioration of gates working under low heads of water. Furthermore, the gearing system of the gates has reached its lifespan, and a motorized gate system is recommended.
4. Serial calibration and validation of both models are necessary with updated datasets from the field to predict extreme conditions and structural modifications.
5. Efficient water management strategies could guarantee fair sharing of the lateral offtakes.
6. For future research and studies, coupling of 1D models with 2D and 3D models is recommended to provide more detail to the hydraulic analysis. Moreover, the lateral distributaries are not integrated into the canal network, which indicates that the model does not consider the downstream submergence of lateral offtakes. Future studies should consider the integration of all the distributaries to comprehensively understand the dynamics of the canal network.

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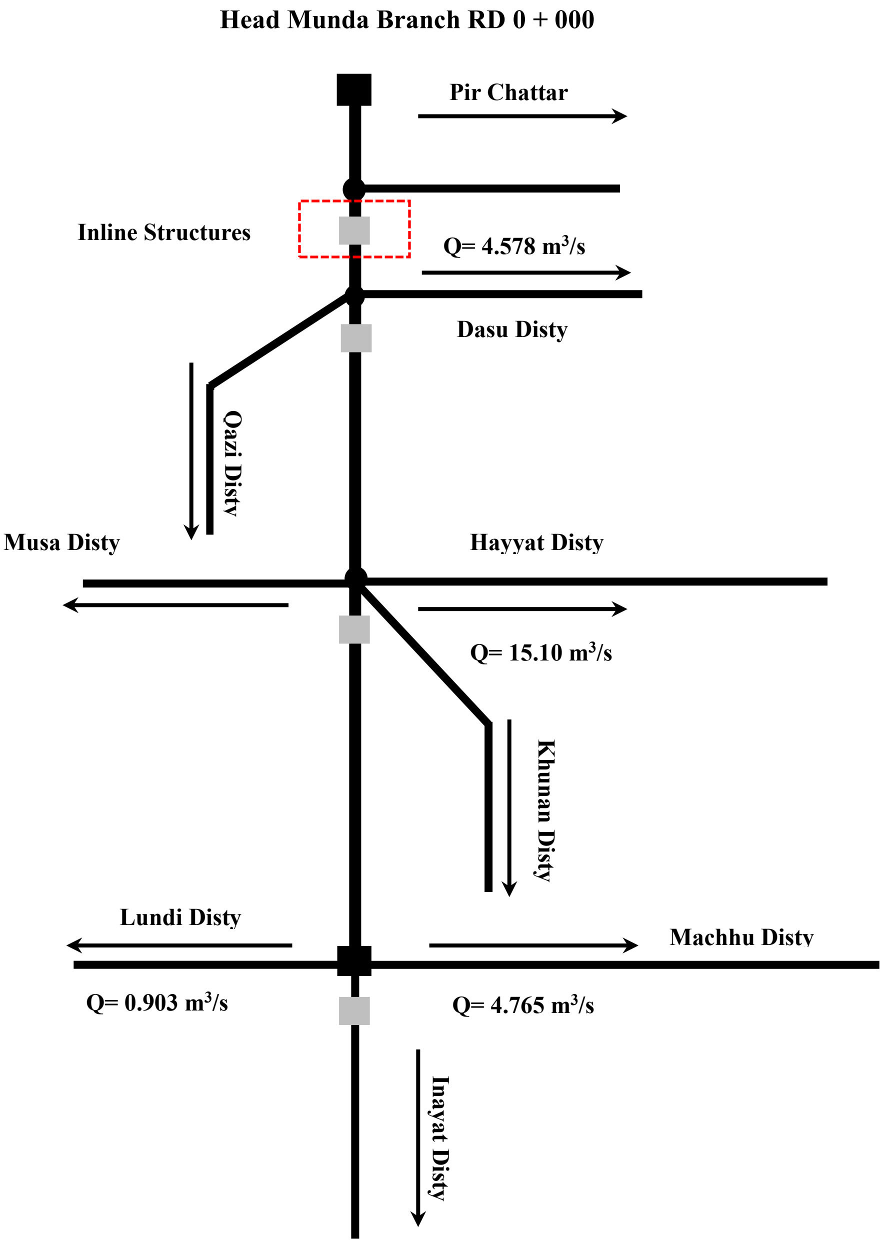
Appendix

Table. A description of the rotational program of Layyah Canal Division for season 2023-24 due to shortage of water in River Indus.

Group	Sr. No	Details of the Channel	Design Discharge (m^3/s)	Indent (m^3/s)	Subgroup	Details of the Channel	Design Discharge (m^3/s)	Indent (m^3/s)
A	1	Machu Disty	4.765	4.765	A1	Machu Disty	4.765	4.765
	2	Dasu Disty	4.578	4.578	A2	Dasu Disty	4.578	4.578
B	1	Inayat Disty	9.919	9.919	B1	Inayat Disty	9.919	9.919
	2	Khunan Disty	0.777	0.777		Khunan Disty	0.777	0.777
	3	Pir Chattar Disty	0.155	0.155		Pir Chattar Disty	0.155	0.155
	4	Musa Disty	1.697	1.697		Musa Disty	1.697	1.697
	5	Qazi Disty	0.498	0.498	B2	Qazi Disty	0.498	0.498
C	1	Hayat Disty	15.10	15.10	C1	Hayat Disty	15.10	15.10
	2	Lundi Disty	0.903	0.903	C2	Lundi Disty	0.903	0.903

From	To	Preference Order					
		1st		2nd		3rd	
09.10.23	16.10.23	B	B2	A	A2	C	C1
17.10.23	24.10.23	C	C2	B	B2	A	A2
25.10.23	01.11.23	A	A1	C	C2	B	B2
02.11.23	09.11.23	B	B1	A	A1	C	C2
10.11.23	17.11.23	C	C1	B	B1	A	A1
18.11.23	25.11.23	A	A2	C	C1	B	B1
26.11.23	02.12.23	B	B2	A	A2	C	C1
03.12.23	10.12.23	C	C2	B	B2	A	A2
11.12.23	18.12.23	A	A1	C	C2	B	B2
19.12.23	26.12.23	B	B1	A	A1	C	C2
27.12.23	03.01.24	C	C1	B	B1	A	A1
04.01.24	11.01.24	A	A2	C	C1	B	B1
12.01.24	19.01.24	B	B2	A	A2	C	C1
20.01.24	27.01.24	C	C2	B	B2	A	A2
28.01.24	04.02.24	A	A1	C	C2	B	B2
05.02.24	12.02.24	B	B1	A	A1	C	C2
13.02.24	20.02.24	C	C1	B	B1	A	A1
21.02.24	28.02.24	A	A2	C	C1	B	B1
29.02.24	07.03.24	B	B2	A	A2	C	C1
08.03.24	15.03.24	C	C2	B	B2	A	A2
16.03.24	23.03.24	A	A1	C	C2	B	B2
24.03.24	31.03.24	B	B1	A	A1	C	C2
01.04.24	08.04.24	C	C1	B	B1	A	A1
09.04.24	16.04.24	A	A2	C	C1	B	B1



Total Discharges at different takeoffs (m^3/s)	**25.49**
Pir Chattar Disty	-
Dasu Disty	4.578
Qazi Disty	-
Hayyat Disty	15.10
Musa Disty	-
Khunan Disty	-
Machuu Disty	4.765
Lundi Disty	0.903
Inayat Disty	-
Total lateral takeoff Discharge	25.34

Discharge Summary (m^3/s)	
Head Discharge	25.49
Total lateral Discharge	25.34
Designed outlet discharge	0.045
Losses as per L section	0.105

Fig. Summary of the field observed discharges at the head and distributaries of the Munda on (13 April 2024)