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ESTIMATING FLOW INEFFICIENCIES IN THE KADDUMURIVU IRRIGATION SYSTEM THROUGH INTEGRATED HYDRODYNAMIC MODELING AND REAL-TIME ON-SITE MEASUREMENTS

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Abstract—Irrigation water scarcity in Sri Lanka is intensified by conveyance losses in unlined tank-cascade canals. This study quantifies flow inefficiencies in a 650 m reach of the Kaddumurivu Irrigation System (KIS) by integrating field measurements with a one-dimensional steady-flow HEC-RAS model. Eight canal stations were surveyed using a Total Station, while discharge and water-surface elevations were measured under steady operating conditions using a current meter and staff gauges. The model was calibrated by adjusting Manning's roughness coefficient until simulated water-surface elevations agreed with observations within ±0.05 m and was subsequently validated using an independent flow dataset. The measured discharge decreased from 1.0052 m^3/s upstream to 0.7681 m^3/s downstream, giving a volumetric loss of 0.2371 m^3/s equivalent to 23.6% of inflow, and a conveyance efficiency of 76.4%. Energy-based analysis gave a total head loss of 0.30 m, of which 0.12 m was attributed to friction and 0.18 m (60%) to non-friction inefficiency. The calibrated Manning's n values were 0.039 for the upper unlined reach, 0.012 for the concrete-lined reach, and 0.020 for the lower unlined reach. Spatial analysis identified the lower unlined reach and short structural-transition segments as critical loss locations. The results suggest that non-friction mechanisms, potentially including seepage, are significant contributors to the observed inefficiency, supporting targeted lining, maintenance, structural inspection, and continued monitoring rather than uniform rehabilitation of the entire canal.

Index Terms—irrigation canal; conveyance loss; HEC-RAS; Manning's roughness; seepage; hydraulic inefficiency; Kaddumurivu Irrigation System

I. INTRODUCTION

Irrigated agriculture accounts for approximately 70% of global freshwater withdrawals, and losses within open conveyance systems directly reduce the water available to downstream users [1]. In South Asia, it is estimated that 30 to 50 percent of water diverted at canal headworks is lost before reaching the tail-end command area, with seepage through unlined earthen channels identified as the predominant mechanism [2]. In Sri Lanka's dry-zone tank-cascade systems, many main canals remain unlined or only partly lined, and conveyance inefficiencies have been documented as a chronic constraint on agricultural productivity [3].

The Kaddumurivu Irrigation System (KIS) is a representative case: its 650 m main-canal study reach contains a 125 m concrete-lined central section between unlined earthen reaches. Following expansion of the command area, tail-end shortages have become a practical concern for farmers in the lower reaches. Previous investigations have identified seepage, evaporation, operational losses, and possible unauthorized abstractions as the principal non-friction mechanisms that may reduce delivery efficiency in such systems [4]. However, no systematic, physically grounded study has been conducted to quantify these losses or determine their underlying causes in the KIS.

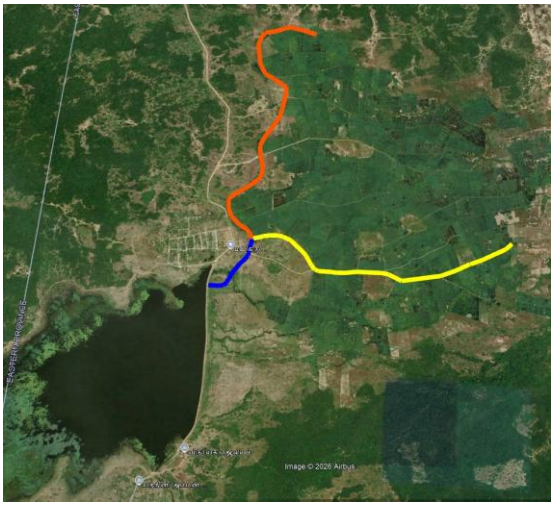


Fig. 1. Kaddumurivu Tank and the main canal study reach.

Conventional inflow-outflow subtraction can quantify the net discharge deficit, but it cannot separate normal hydraulic friction from water that leaves the conveyance system. This distinction is critical because the engineering response differs: friction may be addressed through vegetation and sediment management, whereas seepage may justify lining or other seepage-control measures [5]. The study therefore combines field observations with one-dimensional

hydrodynamic modelling so that the friction component of head loss can be estimated independently from the residual inefficiency.

The aim of this study was to estimate and analyze conveyance losses in the Kaddumurivu main canal by integrating field-based flow measurements with hydrodynamic modelling. The specific objectives were to: (i) survey the canal geometry and hydraulic structures; (ii) measure discharge at eight selected stations under steady operating conditions; (iii) develop, calibrate, and validate a HEC-RAS model using observed geometry and water levels; and (iv) quantify volumetric and energy-based hydraulic inefficiencies. The analysis also examined the concrete-lined reach and pipe culvert as potential hydraulic bottlenecks.

II. RELATED WORK

Water conveyance inefficiency is a persistent constraint in irrigation systems because losses reduce both the quantity and equity of water delivered to farms. Barkhordari and Shahdany [2] conducted a systematic review and documented average water loss rates of 23–35% in the southern United States, 33–200% in Iran, approximately 50% in Portugal, and 35–68% in Pakistan, with the highest values invariably occurring in unlined earthen channels. In India, Kulkarni and Nagarajan [6] estimated that 45% of water diverted at canal headworks fails to reach farm fields. These losses occur primarily through seepage from canal sides and bottom, evaporation from the water surface, and operational losses arising from spills, overtopping, and mismatches between continuous main canal flow and intermittent field irrigation schedules.

Seepage is consistently identified as the largest and most manageable component, especially in alluvial terrains [7]. In Sri Lanka's dry-zone tank cascades, Itakura [3] found that wasteful consumption (seepage plus evaporation) accounted for over 50% of total water use, underscoring the magnitude of avoidable losses in these ancient systems. Wanyama and Bwambale [5] emphasized that while evaporation is difficult to control, seepage represents the major component of water loss and can be effectively managed through engineering interventions such as canal lining.

Several approaches are available for estimating canal losses. The simplest is the inflow-outflow method, which measures the discharge difference between two stations. Although straightforward, this method gives a lump-sum loss and does not explain whether the deficit is caused by seepage, evaporation, diversions, or hydraulic resistance [8]. Ponding tests and empirical seepage equations can provide more direct estimates of seepage, but their applicability may be constrained by local soil properties, operational conditions, and the difficulty of isolating representative reaches [9]. Instrument-based techniques such as acoustic Doppler current profilers can improve point measurements, but their cost and deployment requirements can limit routine use [10].

Hydraulic modelling provides an additional diagnostic capability because it can reproduce water-surface profiles and estimate frictional energy losses from measured geometry and roughness. The American Society of Civil Engineers (ASCE) Task Committee on Irrigation Canal System Hydraulic Modelling [11] demonstrated that mathematical simulation models are essential instruments for improving irrigation water delivery systems' operations and long-term management. Among available tools, HEC-RAS is particularly attractive because it is freely available, extensively validated, and capable of modelling the influence of in-line structures such as gates, weirs, and culverts [12].

Previous studies have demonstrated the value of this approach. Imbenzi et al. [13] applied HEC-RAS to the Mwea Irrigation Scheme in Kenya and reported improvements associated with canal lining and desilting. Umar et al. [14] applied HEC-RAS to the Hakra Branch Canal System in Pakistan to investigate operational performance and head-tail inequities. Zahran et al. [15] confirmed the model's ability to predict water levels and quantify the hydraulic benefits of rehabilitation in Egyptian canals. These studies support the use of calibrated hydraulic models as decision-support tools rather than as substitutes for field measurement.

Ahmed et al. [16] investigated water conveyance losses in the irrigation canal network of Nakada, Qena Governorate, Upper Egypt, using ponding tests and empirical seepage equations. Their results showed that concrete lining reduced total seepage losses by 81%, from an average of 8,301 m^3/day in unlined canals to 1,575 m^3/day in lined sections. Evaporation was found to be negligible, accounting for less than 0.05% of total discharge. These findings have direct relevance to the Kaddumurivu context, where the existing 125 m concrete-lined section provides a site-specific reference condition for comparing loss rates between lined and unlined reaches.

A remaining gap identified in the literature is the limited number of reach-scale studies in Sri Lankan tank-cascade systems that combine accurate field geometry, direct discharge measurements, and hydraulic modelling. The Kaddumurivu investigation addresses this gap at a practical scale, focusing on the main canal to determine where the measurable hydraulic deficit occurs, how much can be explained by friction, and which locations should receive priority for further inspection or rehabilitation.

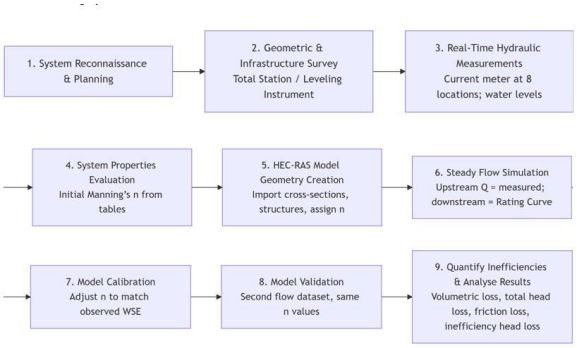


Fig. 2. Overall field measurement, modelling and inefficiency-analysis workflow.

III. METHODOLOGY

The investigation covered a 650 m reach of the main canal, from River Station (RS) 650 upstream to RS 0 downstream. Eight cross-sections were surveyed, including the boundaries of the concrete-lined section and the location of the pipe culvert. Field measurements were carried out under representative steady operating conditions. Cross-sectional geometry was obtained with a Total Station, while discharge was measured using a current meter following the velocity–area method. Water-surface elevations were recorded concurrently to support model calibration.



Fig. 3. Total Station surveying along the Kaddumurivu main canal.

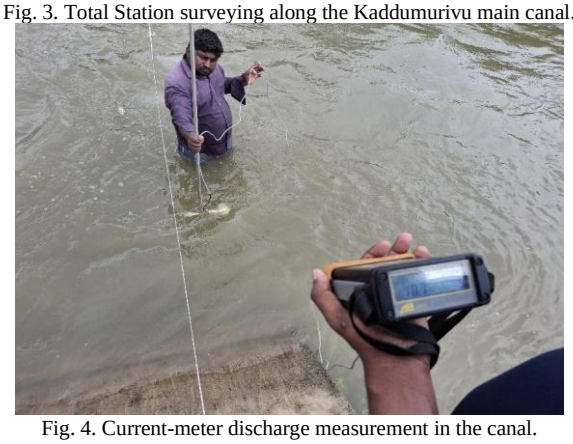


Fig. 4. Current-meter discharge measurement in the canal.

For each measurement station, the channel was divided into vertical segments. Local depth, velocity and partial area were used to calculate partial discharges, which were summed to obtain station discharge. The study also developed a stage–discharge relationship at the downstream gauge using measurements collected over a range of flows. This provided a hydraulic boundary condition for the model.

A one-dimensional steady-flow HEC-RAS model was developed from the surveyed cross-sections. Initial Manning's n values were taken as 0.025 for the earthen reaches and 0.015 for the concrete-lined reach. The upstream boundary was the measured discharge at RS 650 and the downstream boundary was represented by the rating curve. Calibration was performed iteratively by adjusting Manning's n until computed water-surface elevations matched field observations within ±0.05 m. Validation used a second flow dataset without changing the calibrated geometry or roughness values.

Volumetric conveyance loss was calculated from the difference between upstream and downstream discharge. Conveyance efficiency was expressed as the downstream discharge divided by the upstream discharge. For the energy analysis, total head loss was determined from the measured energy heads, while the calibrated HEC-RAS model was used to obtain the friction-only head loss. The difference between total and friction head loss was interpreted as the non-friction inefficiency component.

The station-by-station measurements showed that discharge reduction was concentrated in the unlined reaches and at short structural transitions. The upstream RS 650 station carried 1.0052 m^3/s, while the downstream RS 0 station carried 0.7681 m^3/s. Intermediate stations showed a progressive decline. The concrete-lined section between approximately RS 445 and RS 320 had the smallest loss rate per metre, whereas the lower unlined reach from RS 315 to RS 0 accumulated the largest share of the total volumetric deficit. This pattern is important because it indicates that the canal should not be treated as hydraulically uniform.

The calibrated model reproduced the measured water-surface trend along the study reach and represented the pipe culvert explicitly. The close agreement between computed and observed levels indicates that the selected geometry and calibrated roughness values were adequate for the diagnostic purpose of the study. The independent validation dataset retained the same geometry and roughness parameters, providing an additional check that the calibration was not simply fitted to one field observation set.

TABLE II. SPATIAL DISTRIBUTION OF CONVEYANCE LOSS

Reach	Length (m)	Loss rate ($m^3/s/m$)	Interpretation
RS 650–450	200	0.00046	Unlined; diffuse loss
RS 450–445	5	0.0014	Short transition; investigate
RS 445–320	125	0.00018	Concrete-lined; lowest rate
RS 320–315	5	0.0054	Culvert transition; highest rate
RS 315–0	315	0.00028	Unlined; largest cumulative loss

The reach-scale loss rates demonstrate why spatial analysis is more informative than a single overall efficiency value. The 125 m concrete-lined section has the lowest loss rate, whereas the two 5 m transition

reaches have disproportionately large losses per metre. The 315 m lower unlined reach has a lower unit rate than the upper unlined reach but contributes the largest cumulative loss because of its length. Rehabilitation priorities should therefore consider both unit loss intensity and total recoverable discharge.

IV. RESULTS

The measured flow decreased from 1.0052 m³/s at the upstream end (RS 650) to 0.7681 m³/s at the downstream end (RS 0). Thus, the 650 m reach lost 0.2371 m³/s or 23.6% of the incoming flow, giving a conveyance efficiency of 76.4%. The loss accumulated progressively rather than occurring uniformly along the canal.

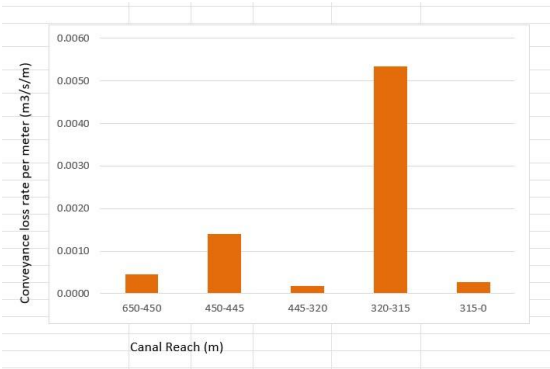


Fig. 5. Conveyance loss rate along the canal sections.

The calibrated Manning's n values were 0.039 for the upper unlined reach (RS 650–450), 0.012 for the concrete-lined midsection (RS 445–320), and 0.020 for the lower unlined reach (RS 315–0). The relatively high upper-reach value is consistent with field observations of vegetation and irregular bed conditions. The low value for the concrete-lined section reflects its smoother hydraulic boundary. The lower unlined reach had a moderate roughness coefficient, indicating that its large water loss cannot be explained by friction alone. The model reproduced observed water-surface elevations within ±0.05 m, and validation with an independent dataset confirmed the model's reliability for diagnostic analysis.

Parameter	Upstream	Downstream	Result
Discharge	1.0052 m³/s	0.7681 m³/s	Loss = 0.2371 m³/s
Conveyance efficiency	—	—	76.4%
Total head loss	101.04 m	100.74 m	0.30 m
Friction head loss	—	—	0.12 m
Inefficiency head loss	—	—	0.18 m (60%)

TABLE I. SUMMARY OF PRINCIPAL HYDRAULIC RESULTS

Table I summarizes the spatial distribution of conveyance losses along the canal reaches. The reach-scale loss rates demonstrate why spatial analysis is more informative than a single overall efficiency value. The 125 m concrete-lined section had the lowest loss rate (0.00018 m³/s/m), whereas the two 5 m transition reaches had disproportionately large losses per metre (0.0014 and 0.0054 m³/s/m). The 315 m lower unlined reach had a lower unit rate than the upper unlined reach but contributed the largest cumulative loss (14.8% of inflow) because of its length.

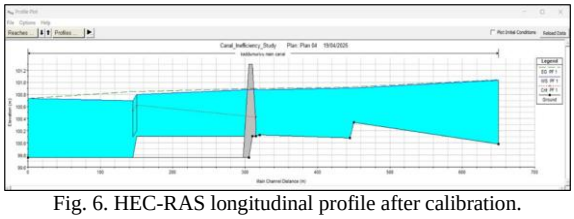


Fig. 6. HEC-RAS longitudinal profile after calibration.

The spatial results identified two short 5 m segments with unusually high loss rates: approximately 0.0014 m³/s/m near the upstream lining transition and 0.0054 m³/s/m around the culvert transition. The lower unlined reach contributed about 14.8% of the inflow as cumulative loss, whereas the concrete-lined reach had a much lower loss rate of about 0.00018 m³/s/m. The sharp local reductions suggest that structural leakage, uncontrolled diversion or transition effects should be investigated separately from diffuse seepage.

The distinction between discharge loss and head loss is central to interpreting the results. A 23.6% reduction in discharge does not mean that 23.6% of the energy loss is caused by one mechanism. The model estimates the frictional component expected from the observed geometry and calibrated boundary roughness, while the field energy balance captures the overall change in total head. The 0.18 m residual therefore represents an energy-based indicator of processes that are not explained by ordinary boundary friction. It should be interpreted diagnostically rather than as a direct measurement of seepage alone, because evaporation, diversions and localized structural losses may also contribute.

The two short high-loss segments require particular attention. The report associates one with the transition into the concrete-lined reach and the other with the pipe-culvert location. Their high loss rates per metre are much larger than the diffuse losses observed elsewhere. A field inspection should therefore verify whether leakage through joints or cracks, an uncontrolled offtake, culvert damage or local geometry is responsible. Correctly identifying these point losses is important because repairing a short defective structure may recover water more efficiently than lining a long reach with comparatively moderate loss.

V. DISCUSSION

The 23.6% volumetric loss is substantial for a small tank-based irrigation scheme because every recovered cubic metre can improve downstream availability. The pattern of loss supports the interpretation that unlined canal sections are the principal weak points. The concrete-lined reach performed considerably better, and its low loss rate provides a useful site-specific benchmark for distinguishing seepage-related loss from ordinary hydraulic resistance.

The calibrated Manning’s n values also reveal differences in physical condition. The upper unlined reach, with n = 0.039, likely reflects vegetation,

sediment deposition and irregular bed conditions. The concrete-lined section, with n = 0.012, is hydraulically smooth. The lower unlined reach, with n = 0.020, has moderate friction but still contributes the largest cumulative discharge loss. Consequently, roughness alone does not explain the observed deficit.

The energy decomposition strengthens this conclusion. Only 40% of the total head loss was reproduced as friction in the calibrated model, while 60% remained as inefficiency. The report attributes this residual primarily to seepage, with smaller possible contributions from evaporation and unauthorized diversions. The result is consistent with the wider literature reviewed in the report, where seepage is commonly identified as the dominant loss mechanism in unlined irrigation canals.

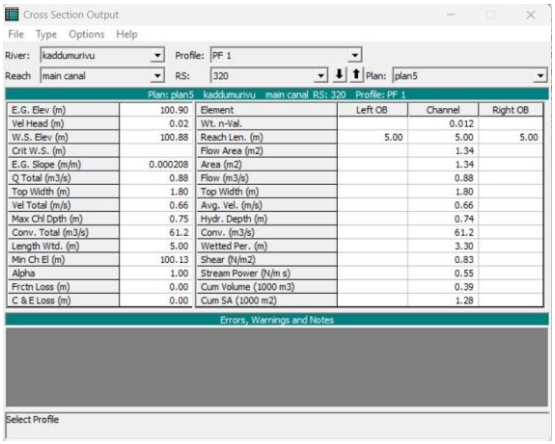


Fig. 7. Calibrated HEC-RAS cross-section at the concrete-lined reach.

The findings are also consistent with the comparative studies discussed in the final report. Previous investigations in irrigation systems in Kenya and Egypt reported substantial improvements following lining and desilting. In the Egyptian study cited in the report, lining reduced seepage losses by 81%. These comparisons do not imply that the same percentage improvement will occur at Kaddumurivu; rather, they support the study's conclusion that targeted lining of high-loss unlined sections is a technically justified intervention to be evaluated.

The study has several limitations. Measurements were obtained under a single principal steady-flow condition, and seepage and Manning's n can vary with season, vegetation, sediment and groundwater conditions. The discharge measurements also contain instrument and field-observation uncertainty. The HEC-RAS representation treats the system as steady flow and therefore does not capture transient responses to gate operation. Local contraction and expansion losses were assumed negligible except where structures were explicitly represented. Finally, the investigation covers only 650 m of the main canal and does not quantify losses in distributaries, field channels or on-farm application.

VI. IMPLICATIONS FOR IRRIGATION MANAGEMENT

The results support a risk-based approach to canal rehabilitation. The measured efficiency of 76.4% indicates that a significant fraction of the upstream discharge does not reach the downstream end, but the spatial analysis shows that the loss is not evenly distributed. A rehabilitation programme should therefore begin with the identified hotspots and the long lower unlined reach rather than treating every metre of the canal as equally defective. This approach can reduce intervention cost while focusing engineering effort where water recovery is most likely.

Targeted lining is the principal structural option suggested by the evidence. The existing 125 m concrete-lined section had the lowest loss rate per metre, approximately 0.00018 $m^3/s/m$, compared with 0.00046 $m^3/s/m$ in the upper unlined reach and 0.00028 $m^3/s/m$ in the lower unlined reach. The comparison indicates a clear local benefit from an impermeable boundary. Nevertheless, lining should be preceded by site-specific economic and geotechnical assessment because the study did not evaluate construction cost, long-term durability or the effect of lining on groundwater interactions.

Maintenance remains important even where lining is not immediately feasible. The upper unlined reach had a calibrated Manning's n of 0.039, considerably higher than the initial value used for a clean earthen channel. Field observations in the report identified vegetation and irregular channel conditions. Vegetation clearing, desilting, bank maintenance and restoration of the intended cross-section can therefore reduce frictional resistance and restore hydraulic capacity. These actions should complement, rather than replace, seepage-control measures in reaches where the dominant problem is water leaving through the bed and banks.

The two short transition reaches should be treated as separate structural investigations. The 450–445 m segment had a loss rate of approximately 0.0014 $m^3/s/m$, while the 320–315 m segment had approximately 0.0054 $m^3/s/m$. Because each segment is only 5 m long, a small physical defect can create a large apparent loss per unit length. Inspection should verify the lining transition, culvert condition, joints, cracks, possible uncontrolled offtakes and local changes in channel geometry. This diagnostic step is important before committing resources to long-reach lining.

Monitoring should be incorporated into future operation. The final research report notes that Manning's n and seepage conditions may vary with vegetation growth, sediment transport and groundwater levels. Repeating discharge and water-level measurements in both wet and dry periods would establish seasonal loss ranges and improve confidence in rehabilitation decisions. The calibrated HEC-RAS model can then be rerun for alternative operating and rehabilitation scenarios, providing a low-cost screening tool before physical works are undertaken.

At a wider scale, the methodology can be extended from the 650 m study reach to interconnected tank systems. Coupling hydraulic modelling with GIS would allow spatial inefficiencies to be compared across multiple canals and tanks and would support prioritization of rehabilitation at the cascade level. Such an extension should retain the field-validation principle used in this study: model outputs should be anchored to observed geometry, discharge and water levels. The result would be a more defensible basis for allocating limited irrigation rehabilitation resources.

VII. CONCLUSION AND RECOMMENDATIONS

The integrated field-measurement and HEC-RAS approach provided a quantitative diagnosis of flow inefficiency in the Kaddumurivu main canal. Under the investigated steady condition, discharge fell from 1.0052 m³/s to 0.7681 m³/s, corresponding to a 23.6% volumetric loss and 76.4% conveyance efficiency. The calibrated model reproduced observed water levels within ±0.05 m and gave Manning's n values of 0.039, 0.012 and 0.020 for the upper unlined, concrete-lined and lower unlined reaches, respectively. Energy analysis showed that 0.18 m, or 60% of the 0.30 m total head loss, was not explained by friction.

The principal recommendation is to prioritize rehabilitation based on measured loss hotspots rather than applying uniform treatment to the whole canal. The lower unlined reach should be assessed for targeted seepage-control measures, while the existing concrete-lined section demonstrates the potential hydraulic benefit of impermeable lining. The two short high-loss transition segments should be physically inspected for leakage, damaged joints, uncontrolled offtakes or culvert-related losses. Routine vegetation clearing and desilting should be maintained where high roughness is observed. Additional flow and water-level monitoring during wet and dry seasons is recommended to establish seasonal loss ranges.

For future work, the calibrated model can be extended to alternative lining, maintenance and operational scenarios before field implementation. A larger monitoring programme should combine repeated current-meter measurements with improved spatial surveying and, where feasible, GIS-based analysis of the wider tank cascade. Such an extension would allow the KIS methodology to be replicated across interconnected irrigation systems and would provide a stronger basis for cost-effective rehabilitation planning.

VIII. ACKNOWLEDGMENT

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IX. REFERENCES

[1] [1] S. Barkhordari and S. M. H. Shahdany, "A systematic approach for estimating water losses in irrigation canals," Water Science and Engineering, 2022, doi:10.1016/j.wse.2022.02.004.

[2] [2] J. S. Imbenzi, B. M. Mutua, and J. M. Raude, "Hydraulic Analysis of Irrigation Canals using HEC-RAS Model: A Case Study of Mwea Irrigation Scheme, Kenya," International Journal of Engineering Research & Technology, 2015.

[3] [3] J. Wanyama and E. Bwambale, "Hydraulic modelling of irrigation canals for improved flow conditions in surface irrigation systems," ISH Journal of Hydraulic Engineering, 2023, doi:10.1080/09715010.2023.2245785.

[4] [4] M. Umar, U. T. Shah, M. Kamran, et al., "Innovative initiative for effective operation and monitoring using HEC-RAS modelling of Hakra Branch Canal System, Pakistan," 2020, doi:10.1002/ird.2524.

[5] [5] H. S. Ahmed, M. O. Khalifa, H. I. Mohamed, and W. M. Elsadek, "Quantifying Seepage and Evaporation Loss Reductions through Canal Lining: A Field Study from Nakada, Egypt," 2025, doi:10.21608/jesaun.2025.378449.1489.

[6] [6] S. Zahran, E. A. Gooda, and N. AbdelMeged, "Modeling Al-Qaraqoul canal before and after rehabilitation using HEC-RAS," 2020.

[7] [7] H. Cunha, D. Loureiro, G. Sousa, D. Covas, and H. Alegre, "A comprehensive water balance methodology for collective irrigation systems," Agricultural Water Management, 223, 105660, 2019, doi:10.1016/j.agwat.2019.05.044.

[8] [8] G. P. Fipps and R. W. Skaggs, "Effect of canal seepage on drainage to parallel drains," Transactions of the ASABE, 29(5), 1278–1283, 1986, doi:10.13031/2013.30309.

[9] [9] G. P. Garg and A. S. Chawla, "Seepage from trapezoidal channels," Journal of the Irrigation and Drainage Division, 96(6), 1261–1282, 1970, doi:10.1061/JYCEAJ.0002514.

[10] [10] M. E. Grismer, "Point- and reach-scale measurements are important for determining accurate seepage rates in controlled flow channels," California Agriculture, 75(2), 74–82, 2021, doi:10.3733/ca2021a0013.

[11] [11] A. Mohammadi, A. P. Rizi, and N. Abbasi, "Field measurement and analysis of water losses at the main and tertiary levels of irrigation canals: Varamin Irrigation Scheme, Iran," 2019, doi:10.1016/j.gecco.2019.e0064666.

[12] [12] S. Akbar, A. Abbas, M. A. Hanjra, and S. Khan, "Structured analysis of seepage losses in irrigation supply channels for cost-effective investments," Irrigation Science, 31, 2013, doi:10.1007/s00271-011-0290-4.