JWMM

Modeling Optimal Canal Conveyance Capacity for the Ahero Irrigation Scheme using the Hydrologic Engineering Centre River Analysis System (HEC-RAS)

Justus W. Owino, Basil. T. Ong'or, and Micah M. Mukolwe (2023)
Masinde Muliro University of Science and Technology, Kenya

DOI: https://doi.org/10.14796/JWMM.C510

ABSTRACT

Irrigation plays a critical role in addressing food security as envisaged in Kenya's development blueprint, the Big Four Agenda. However, the performance of any open channel irrigation system is a function of its canal conveyance efficiency, among other factors. To overcome challenges with irrigation water conveyance at the Ahero Irrigation Scheme, a Hydrologic Engineering Centre River Analysis System (HEC-RAS) model was used to simulate the flow characteristics at the tail-end section of the canal network, covering a total length of 2.6 km. The study also consisted of a comparative review of an FAO-CROPWAT model estimation water requirement for rice. The manual estimation of the canal capacity in its unmaintained state revealed a discharge capacity of 0.228 m^3/s, which was significantly lower than the minimum crop water demand requirement estimation of 0.3166 m^3/s (a 28% water deficit). The simulated characteristics projected an optimal flow capacity of 0.583 m^3/s. The study recommends canal maintenance (levelling bed undulations, dredging, and smooth concrete lining) to attain the optimal flow capacity at the tail end of the network.

1. INTRODUCTION

Irrigation schemes are mainly used to distribute irrigation water over farmlands, especially during the dry seasons. Largely, the systems utilise either open channels, pipelines, or a mix of the two. Numerous systems are progressively using pipes and more

Owino, J.W., B. Ong'or, and M.M. Mukolwe. 2023. "Modeling Optimal Canal Conveyance Capacity for the Ahero Irrigation Scheme using the Hydrologic Engineering Centre River Analysis System (HEC-RAS)." *Journal of Water Management Modeling* 31: C510. https://doi.org/10.14796/JWMM.C510
www.chijournal.org ISSN: 2292-6062

sophisticated irrigation technologies such as drip and sprinkler, which have reduced water loss due to evaporation, less safety issues, and the capacity to enhance flow via pumping (Chartzoulakis and Bertaki 2015). However, the primary disadvantages of pipelines are their expense and the difficulty of accessing or servicing their interiors, despite the fact that contemporary pipelines often require little maintenance. Moreover, certain crop varieties, such as rice, require flooding or basin irrigation, limiting the usability of pipelines in such contexts.

Open and earthen channels are still popularly used in irrigated agriculture since the system can be easily cleansed of debris, and the cost of upgrading or extending the system is lower than the piped irrigation systems. However, the open earthen canals require frequent and effective maintenance, failure of which leads to them operating below their optimal design capacities. Design and support decision models such as those developed from HEC-RAS can be used for advising on the type of maintenance and schedules for large and complex irrigation schemes. HEC-RAS is an open-source hydraulic modeling program that was developed by the Hydraulic Engineering Centre of the U.S. Army Corps of Engineers (Ardıçlıoğlu and Kuriqi 2019). The model employs a quasi-two-dimensional (2-D) technique to enable elements of water conveyance infrastructure to be incorporated into simulations of open channel systems (Patel et al. 2017). The model has therefore found widespread use in system analysis and upgrade feasibility studies, flood mitigation, inundation, and design studies, including renovation of existing channels to maintain ecological objectives (Patel et al. 2017). HEC-RAS can be used to cost-effectively and promptly evaluate the existing performance of hydraulic systems, while undertaking scenario analysis by assessing the effects of the channel sizes, varying flow rates, and channel surface roughness on the hydraulic characteristics of a canal.

As envisioned in one of the Kenyan government's Big Four Agenda items on agriculture and food security, irrigation plays a critical role in addressing food insecurity by increasing crop productivity, enhancing stable food supply, and mitigating vulnerability to climate change impacts (Ingutia and Sumelius 2022). Irrigated agriculture allows for multiple cropping cycles in a year, eliminating reliance on rain-fed cropping cycles. As such, irrigated agriculture in Kenya provides a buffer against climate change uncertainties, and ensures food security. Further, with Kenya being a water scarce country, the available freshwater resources for irrigation are becoming limited due to pollution and competition from other water uses. Moreover, conveyance losses imply limited water availability for the tail-end users of irrigation water, compromising the crop yields. It is on this backdrop that it has become increasingly important to address irrigation water losses through conveyance inefficiencies. Concisely, addressing canal conveyance losses and inefficiencies in Kenya's open irrigation systems increases food productivity, ensures food security, and conserves fresh water.

Canal conveyance losses minimize the amount of water available for paddy irrigation at the Ahero Irrigation Scheme in Kisumu County, Kenya. This is because irrigation canal hydraulic losses reduce the quantity of water that is available for irrigation (Muema 2018). Under-yields and conflicts over the limited water delivered at the tail-end of the network thus characterize the scheme. The inadequacy of water in the scheme is attributable to the poor hydraulic capacity performance of the canals, coupled with infrastructure breakdown (Chartzoulakis and Bertaki 2015). Moreover, inadequate water management practices within the scheme result in high rice production costs and production deficits (Onyango 2014). For instance, the National Irrigation Board (NIB) spends about KS 22 million annually to pump water to the Western Kenya Irrigation Schemes (Ahero and West Kano) only to produce less than 50% of the targeted rice yields (Alal 2019). Irrigation canal design concerns, and notably ineffective water conveyance to the paddy fields, are some of the causes of the declining rice production levels.

The high-water diversion rates from the source (River Nyando) contribute to the depletion of the water resource. Conversely, the emphasis should be on maximizing the sustainable use of water from the source while minimizing water source extraction. Additionally, severe seepage losses raise the water table, which can cause salinity and sodicity problems that reduce crop yields (Nam et al. 2016). As the water tables rise, the groundwater from the canals picks up salts and other chemicals from aquifers back to the water sources, resulting in groundwater contamination and water quality deterioration. The current study, therefore, aims to identify conveyance inefficiencies and crop water requirement deficits at the tail end of the Ahero Irrigation Scheme network, and uses HEC-RAS as an SDT to improve the infrastructure's overall conveyance capacity.

2. MATERIALS AND METHODS

The study methodology was three-pronged. The first step involved a comparative review of the recently published studies on FAO-CROPWAT research of irrigated rice fields with similar climatic characteristics. The second step entailed an estimation of the actual flow conditions of the scheme canals in their unmaintained state. The final step was a simulation of the flow characteristics at the tail-end of the scheme using HEC-RAS. Data collection for the manual calculation and simulation was based on the tail-end section of Branch Canal 1, at the Ahero Irrigation Scheme. Branch Canal 1 has an approximate length of 2600 m downstream. Purposive sampling was used to identify 26 sampling points or reach stations (RSs) placed at intervals of 100 m along the branch. The research team used Leica Runner 24 dumpy level to collect cross-section data on the inverted levels at each of the 26 reach stations. The discharge and velocity of water in the canal were determined using a digital velocity meter (PCA/VA25), complemented by the use of installed weirs and the area-velocity method.

Manual estimation of the canal capacity was conducted using the standard Manning's equation:

$$Q = VA = \left(\frac{1.00}{n}\right) AR_{\frac{2}{3}} \sqrt{S} \quad (1)$$

Where:

Q = flow rate,

V = velocity of the flow,

A = cross-sectional area of the flow,

n = Manning's roughness coefficient,

R = hydraulic radius, and

S = channel bed slope.

The geometric data collected for both manual estimation and simulation included the shape and type of channel, the channel width, the average Manning's coefficient (n), the side slope, and the channel bed slope (S).

2.1 Data Input and Model Execution

Input data collected for the HEC-RAS model execution included the channel cross-section geometry at each of the 26 reach stations, discharge data, slope (S), and the side slope. During the execution, the geometry data was fed into the HEC-RAS's geometry data editor, with the cross-section cut lines (reach stations) covering the channel's width drawn in a straight line perpendicular to the canal's flow (Figure 1). Figure 2 is a screenshot of the cross-section geometry data entered into the HEC-RAS data monitor. Data collected from all seven cross-section points at the reach stations were entered into the HEC-RAS geometric data editor. A downstream length of 100 m was entered for all station data entries, and the main channel bank values, which varied for each reach stations, were entered. Contraction and expansion factors of 0.1 and 0.3, respectively, were entered for all the reach stations in the HEC-RAS's cross-section data editor. Manning's roughness coefficients of between 0.05 and 0.08 were entered for different reach stations depending on the severity of the roughness, rugosity and underbrush, as determined using Chow's (1959) guidelines on the Manning's values.

Figure 1 Reach stations in the data monitor during execution.

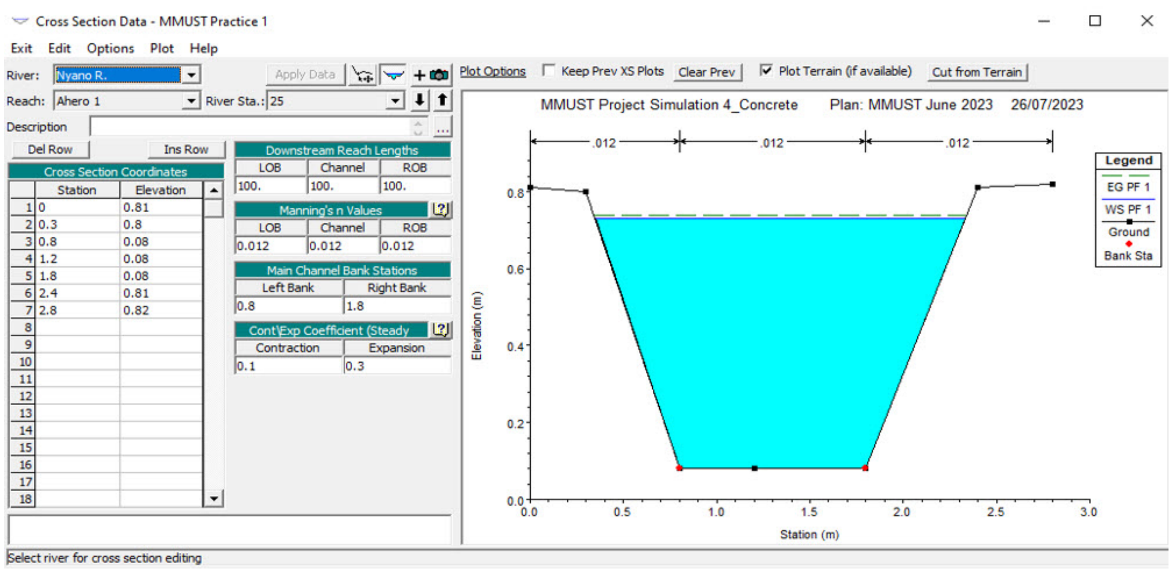

Figure 2 Cross-section data entry into HEC-RAS editor.

A 2D steady flow HEC-RAS model was used during the study. The execution in this study preferred a 2D steady flow over a 1D unsteady flow model, mainly because of the applicability of steady flow with relatively uniform flow characteristics, applicability in scenarios where limited waves are generated, and suitability in scenarios where flow occurs under gravity. At the time of study, the flow at the Ahero Irrigation Scheme canals was relatively uniform, with a gentle slope that enabled flow due to gravity. Moreover, the canal network was less dynamic, with limited chances of generating waves and flash flooding. These factors justified the suitability of steady flow over unsteady flow in the

HEC-RAS model execution for the current study. The running of the model was based on a subcritical steady flow analysis, requiring inputting of the boundary conditions (discharge and slope values) collected from the reach stations. The execution is summarised in the flow chart in Figure 3.

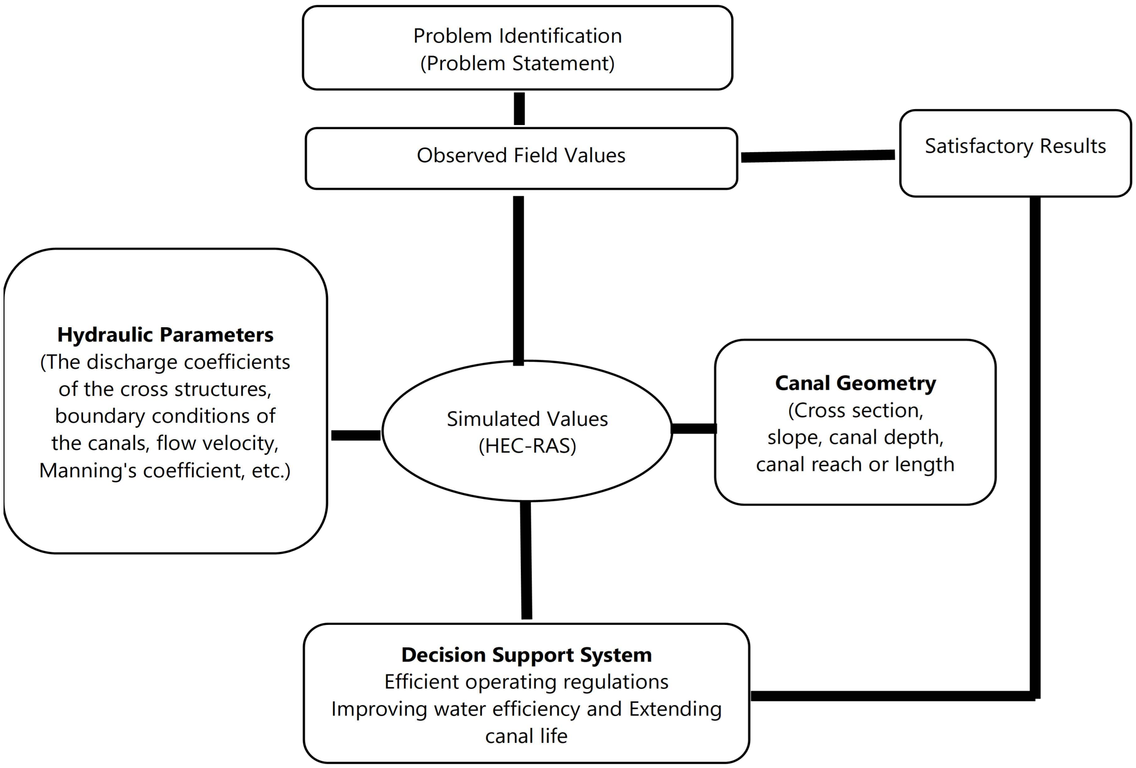

Figure 3 Flow diagram guiding HEC-RAS execution and simulation.

2.2 Model evaluation and validation

The performance of a HEC-RAS model in a study can be validated using indicators that show the ratio of actual to simulated situation (Kumar et al. 2002). The current study employed the coefficient of determination (R^2) for the model validation. This was achieved through a regression analysis of the measured versus simulated depths. The soundness of the model was determined in relation to the goodness-of-fit values recommended by Kamran et al. (2021).

2.3 Comparative literature review for the FAO CROPWAT value

A comparative literature review analysis was conducted on FAO-CROPWAT literature to identify the range of values to be used for the calculation of the best flow scenario for the optimal rice water requirement. The process entailed searching the relevant literature from search databases, mainly Google Scholar and JSTOR. The following keywords were used to facilitate the search; FAO-CROPWAT, rice, water requirement, irrigation, Kenya, and Ahero. Boolean operators (AND, and OR) were used to construct effective searches within the search engines. Inclusion and exclusion criteria included the date of publication, geographical focus, climatic focus, and relevance of the content to the research topic. Thus, recent studies on FAO-CROPWAT water requirements for rice (with a ten-year time range), conducted in near-similar geographical and climatic scenarios as the Ahero Irrigation Scheme, were considered for review.

3. RESULTS AND DISCUSSION

The data collected for manual estimation are tabulated as follows:

Table 1 Channel geometric observed data.

Design Aspect	Data
Type of channel	Earth canal
Channel shape (original design)	Trapezoidal
Channel bottom width	1.2 m
Side Slope (average)	19.89
Depth of flow (average)	0.5527 m
Bed Slope (S)	0.0017
Manning's coefficient (*n*)	0.06

Based on the collected data above, the channel flow area (A), and hydraulic radius (R) were determined as 0.7737 m^2 and 0.281 m, respectively. The actual velocity of flow, as determined on site, ranged from 0.3 m/s to 0.5 m/s (against the design velocity of up to 1.1 m/s for firm clay and gravel). The calculated average channel flow capacity (using Manning's equation) was 0.228 m^3/s.

The comparative review of the relevant literature on FAO CROPWAT values is given in Table 2.

Table 2 Findings from the FAO-CROPWAT reviewed studies.

Authors and Year	Title	Study Area	Findings
Muema et al. (2018)	Application of Benchmarking and Principal Component Analysis in Measuring Performance of Public Irrigation Schemes in Kenya	West Kano Irrigation Scheme	Supplied depths of between 778.5 mm and 1123.8 mm
Too et al. (2019)	Analysis of Water Use in Rice Production under Paddy System and SRI in Ahero Irrigation Scheme, Kenya	Ahero Irrigation Scheme	Total gross irrigation of 934.9 mm was reported.
Rose et al. (2019)	Application of FAO-CROPWAT software for modelling irrigation schedule of rice in Rwanda	Muvumba P-8 marshland in Rwanda	The total gross irrigation was reported at 906.9 mm while the net irrigation was 634.8 mm.
Hossain et al. (2017)	Irrigation Scheduling of Rice (Oryza sativa L.) Using CROPWAT Model in the Western Region of Bangladesh	Western Region of Bangladesh	The study reported a total gross irrigation requirement of 1212 mm.
Bouraima et al. (2015)	Irrigation water requirements of rice using the CROPWAT model in Northern Benin	Northern Benin	The crop water requirement for rice was 920 mm.

The FAO CROPWAT model results in Table 2 suggested near similarities in the rice water requirement of between 778.5 mm to 1212 mm. However, this variance was based on a host of factors, key among them the season in which the research was conducted. Research conducted during dry seasons revealed a high crop water requirement (Hossain et al. 2017), while those conducted during the rainy seasons revealed low crop water requirements for rice (Muema et al. 2018). Too et al.'s (2019) study was conducted between April and July, with similar weather conditions as the current study data collection period. As such, the current study adopted the CROPWAT values of 934.9 mm reported for the area by Too et al. (2019). The other findings (Bouraima et al. 2015; Muema et al. 2018) support the range of CROPWAT values for rice, evidencing insignificant deviation from the used value of 934.9 mm.

With the CROPWAT model estimation requirement of 934.9 mm for rice, the minimal water requirement and flow capacities for the study were estimated for comparison with the manually calculated values. At approximately 70% efficiency, the flow at the tail-end section of the scheme was estimated at 0.3166 m^3/s (1 mm = 10 m^3/ha/year). This estimation was based on the approximate lower scheme total area of about 2629 acres.

A comparative analysis of the manually calculated flow capacity (0.228 m^3/s) and the estimated flow requirement (0.3166 m^3/s using CROPWAT simulation values) suggests a 28% water deficit in canal flows at the tail-end section of the scheme. This is a significant deficit considering that the data was collected between April and July, a period of considerable rainfall and capacity canal flows.

3.1 Simulating the canal capacities using HEC-RAS

The HEC-RAS simulation was conducted using data gathered from the tail-end section of the scheme to bridge the crop water requirement gap, as suggested in the comparative analysis between manual analysis and CROPWAT value estimations. The simulation data was gathered from 26 RSs in the last 2.6 km of the canal. The following data was collected from the field for execution:

Table 3 Data collected for simulation.

Reach	Distance	Flow (m^3/s)	Mean Bed Slope	Manning's Coefficient		
				Min	Normal	Max
Branch Canal 1	+2500	0.171	0.0017	0.050	0.080	0.120
	+2400	0.189	0.0017			
	+2300	0.188	0.0016			
	+2200	0.209	0.0016			
	+2100	0.216	0.0017			
	+2000	0.170	0.0017			
	+1900	0.191	0.0016			
	+1800	0.195	0.0016			
	+1700	0.189	0.0017			
	+1600	0.213	0.0018			
	+1500	0.217	0.0018			
	+1400	0.208	0.0017			
	+1300	0.198	0.0017			
	+1200	0.284	0.0017			
	+1100	0.209	0.0017			
	+1000	0.240	0.0016			
	+900	0.245	0.0017			
	+800	0.205	0.0016			
	+700	0.216	0.0017			
	+600	0.264	0.0018			
	+500	0.289	0.0017			
	+400	0.304	0.0017			
	+300	0.238	0.0016			
	+200	0.288	0.0019			
	+100	0.305	0.0019			
	+000	0.295	0.0017			

An average bed slope value of 0.0017 was used for HEC-RAS execution across all the reach stations. Reach station intervals of 100 metres were used following a recommendation in the HEC-RAS manual that the intervals should not be large in small channels to ensure that the computing method does not become unstable, and cause instability in balancing the energy between the RSs (USACE 2016). For the Branch Canal 1 simulation, RSs were placed at intervals of 100 metres. A straight line perpendicular to the canal's flow was used to construct cross-section cut lines that covered the channels' width. Roughness coefficient values between 0.050 and 0.080 were applied in the simulation, based on the presumption that the channel conditions fall in Chow's (1959) category *e* (unmaintained channels with underbrush). Figure 4 shows the unmaintained section of the canal network at the time of data collection. The image reveals excessive underbrush and the growth of weeds on the channel banks, which justifies the use of channel roughness of between 0.050 and 0.080.

Figure 4 Canal network with excessive underbrush and weeds.

3.2 Calibration and optimisation

The discharges via the gate opening in the gated weirs for both the inline and lateral structures of the canals are adjusted to achieve optimization. The hydraulic model assumes that the entire flow is discharged from the canal system in the current study. As a result, the model rarely took into account how downstream submergence might affect the lateral structures along the canal reach. In this case, the calculated design discharges may be relatively higher than the actual discharges. Therefore, it was necessary to include the actual downstream discharge control conditions through calibration or by design calculations to effectively resolve such differences.

3.3 Expansion and contraction factor

The contraction and expansion coefficients for the reach simulation were based on the constant values of 0.1 and 0.3, respectively, as per the recommendations in the HEC-RAS 5.0 manual (Kamran et al. 2021). As a result, it was expected that changing the coefficients had a limited impact on the model's ability to simulate flows because there are no significant expansion and contraction losses that occurred across the uniform section of the reach. This presumption is consistent with earlier findings by Giovannettone (2008), who studied the St. Clair River in Michigan, Serede et al. (2015), who studied Mwea Irrigation Scheme in Kenya, and Kamran et al. (2021), who studied the Hakra Branch Canal System in Pakistan. Bridges and other barriers and obstructions, as well as straightforward channel control systems (such as weirs), did not significantly increase contraction and expansion losses in any of these cases.

3.4 Model evaluation and validation

The suitability of the model was validated through a regression analysis of the set of observed data and the new simulated values. The regression analysis of the measured versus simulated depths conducted to validate the model suitability yielded the results in Figure 5.

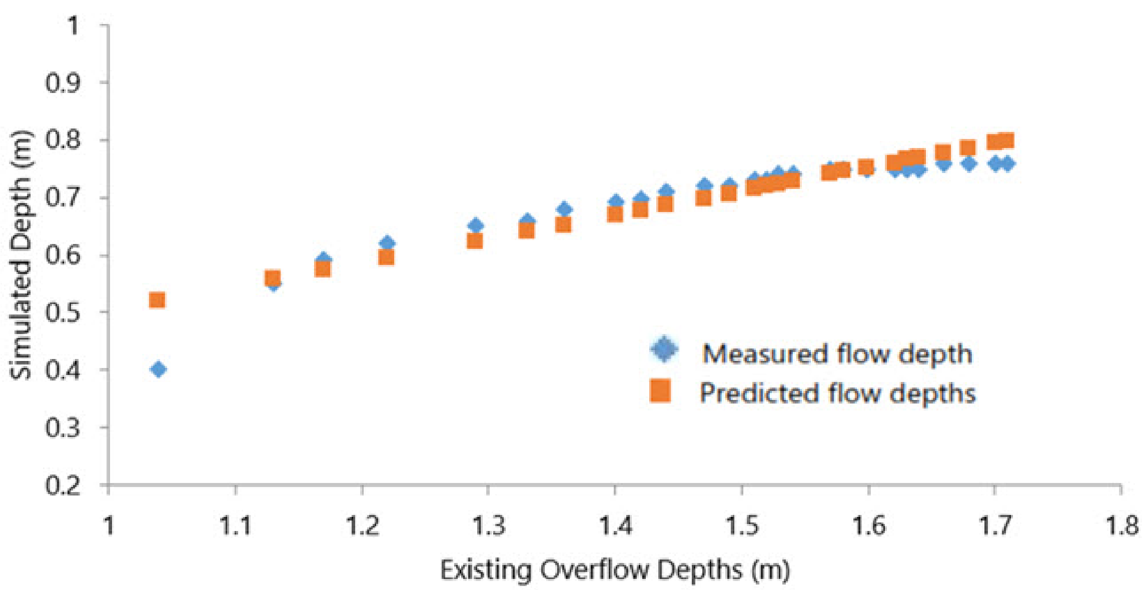

Figure 5 Coefficient of determination for the observed versus simulated depths.

The analysis showed a significant coefficient of determination value (R^2 = 0.857). This implied that the ratio of the actual to the simulated depths had more than 85% goodness-of-fit. The results satisfy the Kamran et al. (2021) condition that a model's coefficient of determination (R^2) should be greater than 0.75, as this yields a satisfactory correlation between the measured versus simulated depths. The model simulation was thus validated as suitable for the current studies.

3.5 Selected cross-sectional extracts of the simulated results

The results (Figures 6 to 9) reveal non-uniformity of the channels regarding their channel depths, channel bottom, and top widths. For instance, the first cross-section (RS 0) data shows a top width of 2 m, a channel bottom width of about 0.5 m, and a depth of about 1.2 m. This data is significantly different from those of the RS 25 (last station) with a channel top width of about 2.3 m, bottom width of about 0.8 metres, and a channel depth of about 3.5 m. The variations may attest to the levels of dilapidation of the channel at different sections depending on the features such as the longitudinal slope, cross-sectional shape, and longitudinal uniformity. All the reach stations sampled here suggest that the channel sections in their current state, cannot carry the simulated irrigation water capacity as evidenced by the entire bank over-flooding.

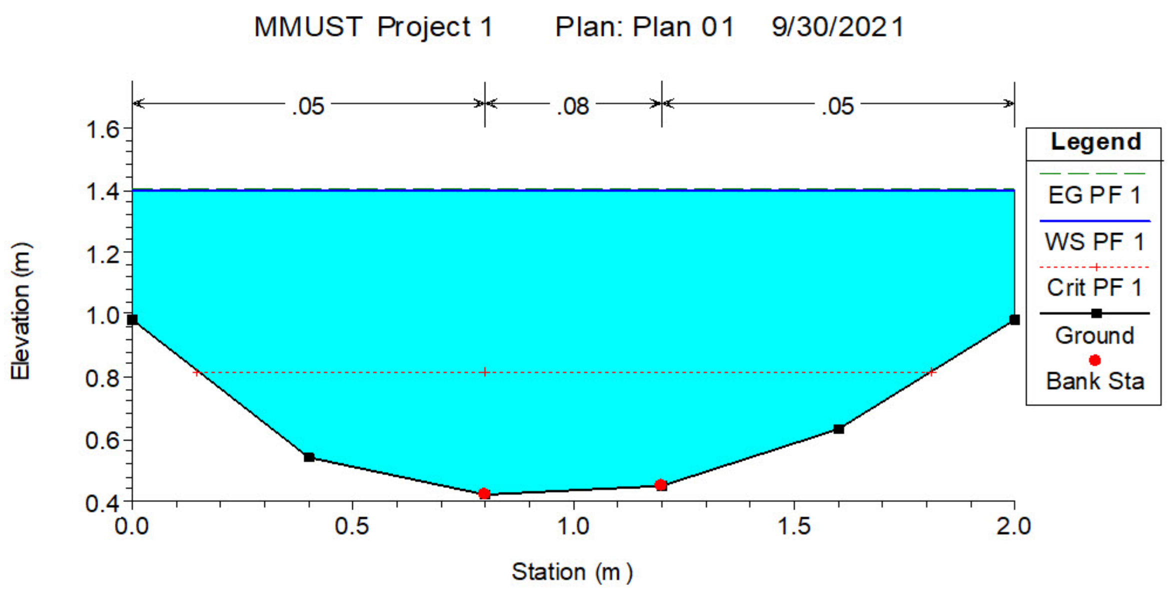

Figure 6 RS 0.

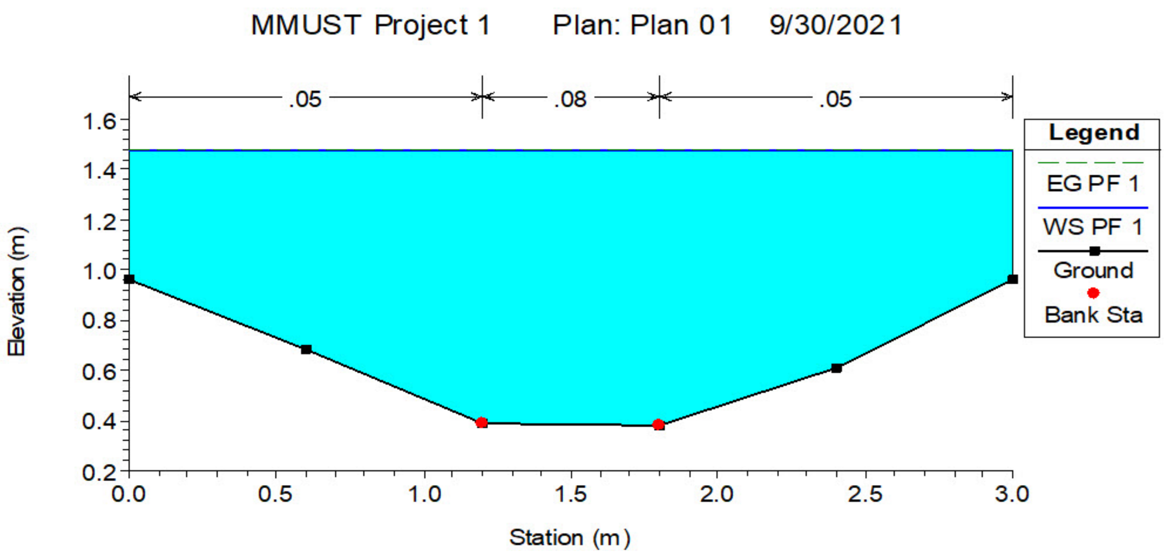

Figure 7 RS 1.

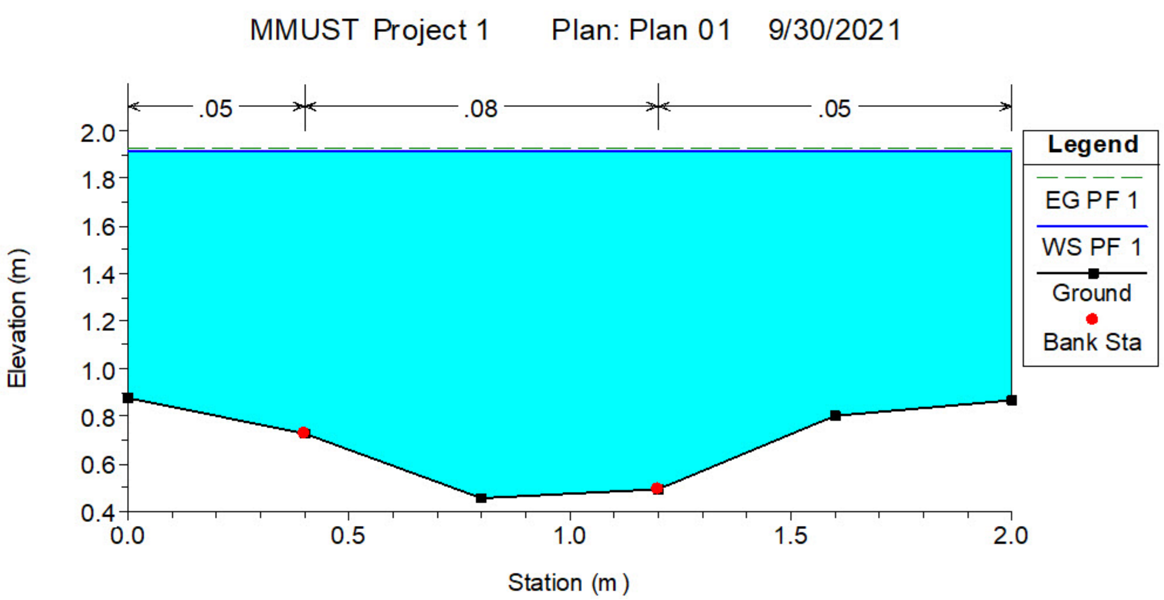

Figure 8 RS 10.

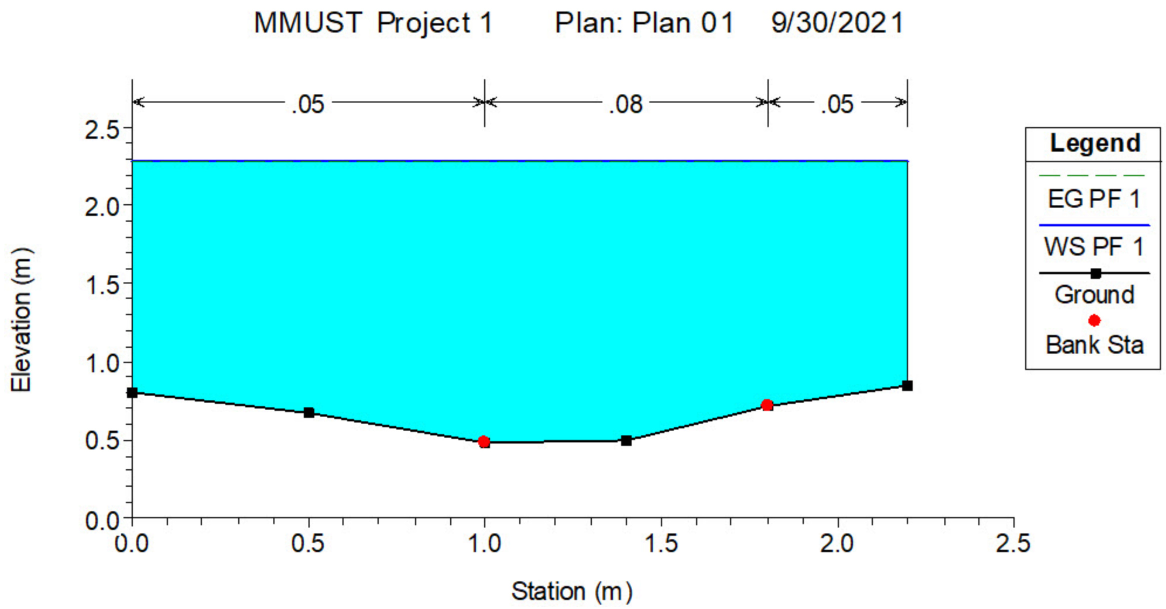

Figure 9 RS 25.

More information from the simulation, and for decision support, is contained in Figures 10 and 11, as extracted from the HEC-RAS simulation window.

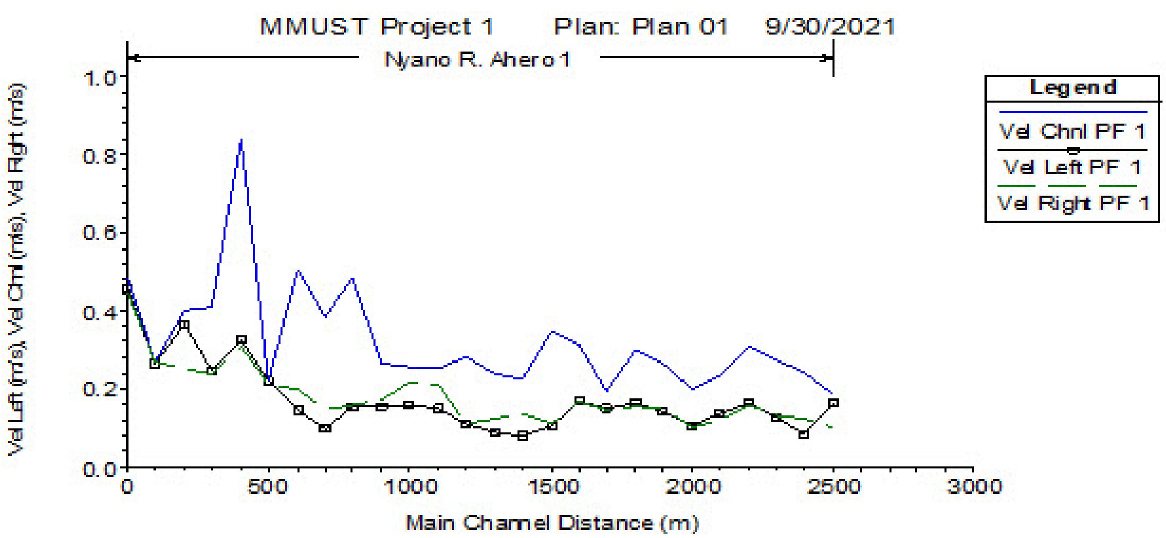

Figure 10 General velocity profile plots.

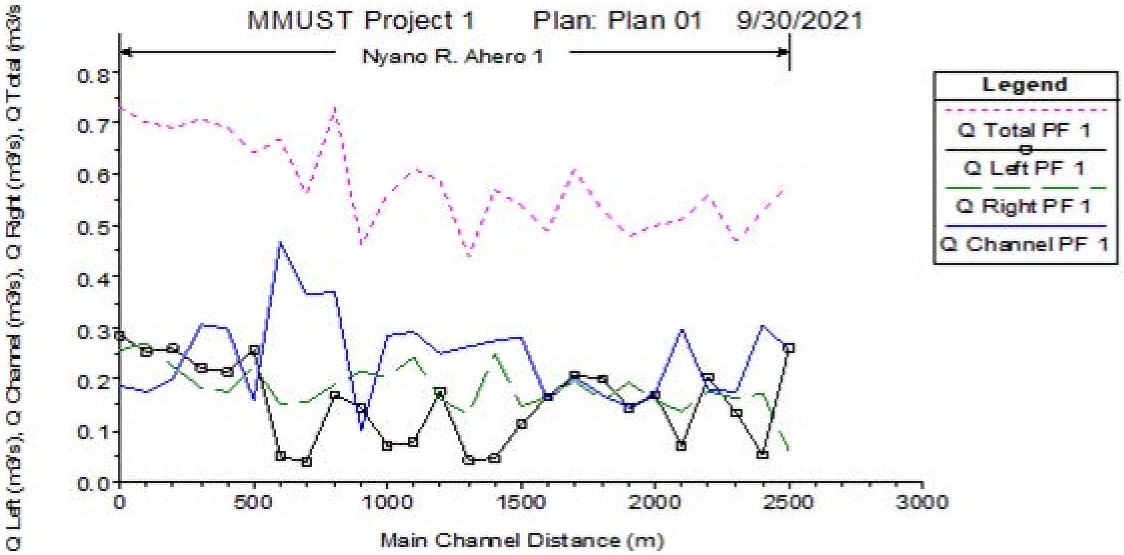

Figure 11 General flow profile plots.

The simulated characteristics projected an optimal flow capacity of between 0.47 and 0.73 m^3/s at the tail-end, or an average of 0.583 m^3/s flow within the canal area (Figures 10 and 11). These simulated flow values are significantly above the manually calculated flow values (average of 39% deficit). The simulated flow results imply that the current flow to the tail-end of the scheme is not only lower than the crop water requirements, but also significantly lower than the optimal canal design discharges. The current discharge values (0.228 m^3/s) are less than half the (simulated) average optimal flow capacity of 0.583 m^3/s expected within the network.

4. CONCLUSION AND RECOMMENDATION

The study's findings suggest that the canal network can no longer carry the design discharges; the earthen canals have lost their optimal design values over time. The measured flow rate during the study (0.228 m^3/s) is significantly lower than the crop water requirement flow rate (0.312 m^3/s) and the predicted flow rates (0.58 m^3/s). From the comparative analysis, the canal network lacks sufficient capacity to convey water to the paddies, since it experiences bank overflows upstream. To deliver sufficient water to the paddies, and to meet the crop water demand at the tail end section of the scheme, the carrying capacity of the canal must be improved by at least 40%. Achieving the 40% improvement in flows means, among others, introducing precise maintenance practices that focus on addressing the undulating channel bed depths, the widening channel top width, the channel underbrush, and lining the channel walls to improve the Manning's value.

Thus, the findings of the study have practical implications with regards to maintenance of open channel irrigation networks. Irrigation schemes with poorly maintained earthen canal networks that are characterized by undulating channel beds, underbrush, irregular and unlined channel walls tend to experience more conveyance losses than those with lined or compacted walls. With the infrastructural dilapidation, these channels experience bank over-flooding upstream, implying limited water for the downstream users. Effective and precise maintenance activities conducted on irrigation canal networks should therefore seek to regularize the channel walls and lower the Manning's value by either compacting the walls or lining them with smooth concrete. Compacting, regularizing. or lining the canal walls with concrete optimizes the flow velocity within the channel, eliminating siltation and eventual bed undulation that is due to velocities lower than 0.65m/s.

For short-term maintenance practices, effective removal of the undergrowth, dredging of the channel bottom, side slopes, and banks may be required to improve the flow velocity and channel uniformity. The long-term solution may, however, require lining the main canal with concrete (trowel finish) to achieve lower Manning's roughness coefficient, and improve flow velocity and discharge along the entire section of the canal to the tail-end. The lining of the canal with concrete will help enhance the uniformity of the canal with regards to the channel bottom width, and cross-section shape, and minimize channel undulations and dilapidation of the side-slopes, which significantly limit the optimal hydraulic performance of the canals.

ACKNOWLEDGEMENTS

The first author would like to gratefully appreciate and acknowledge the Faculty and Postgraduate Program students at the Department of Civil and Structural Engineering of the Masinde Muliro University of Science and Technology (MMUST) for their support during their studies. The author also acknowledges the department of Water and Wastewater Engineering at the Kenya Water Institute for providing some of the equipment support for data collection and analysis.

CONFLICT OF INTEREST STATEMENT

The authors of this article report no potential conflict of interest to declare.

REFERENCES

Alal, M. 2019. “Gravity system to lower high rice irrigation cost.” The Star Newspaper.” Accessed 2023 Jan 17. https://www.the-star.co.ke/counties/rift-valley/2019-03-19-gravity-systems-to-lower-high-rice-irrigation-costs--official/

Ardıçlıoğlu, M., and A. Kuriqi. 2019. “Calibration of channel roughness in intermittent rivers using HEC-RAS model: case of Sarimsakli Creek, Turkey.” *SN Applied Science* 1 (1080): 729–738.

Bouraima, A.K., W. Zhang, and C. Wei. 2015. “Irrigation water requirements of rice using CROPWAT model in Northern Benin.” International Journal of Agricultural and Biological Engineering 8 (2): 58–64.

Chartzoulakis, K., and M. Bertaki. 2015. “Sustainable water management in agriculture under climate change.” *Agriculture and Agricultural Science Procedia* 4 (1): 88–98.

Chow, V.T. 1959. *Open channel hydraulics.* New York (NY): McGraw-Hill.

Giovannettone, J.P. 2008. “Preparation of the 1-D St. Clair River HEC-RAS model in order to study changes in river conveyance and morphology.” *Environmental Science* 1: 4–43.

Hossain, M.B., M.S. Yesmin, M.N. Maniruzzaman, and J.C. Biswas. 2017. “Irrigation scheduling of rice (Oryza sativa L.) using CROPWAT model in the western region of Bangladesh.” *The Agriculturists* 15 (1): 19–27.

Ingutia, R., and J. Sumelius. 2022. “Determinants of food security status with reference to women farmers in rural Kenya.” *Scientific African* 15 (e01114): 1–15.

Kamran, M., W. Yousaf, R. Rajapakse, A. Kareem, M. Riaz, M. Asif, M. Umar, et al. 2021. “Innovative initiative for effective operation and monitoring using HEC-RAS modelling of Hakra Branch Canal System, Pakistan.” *Irrigation and Drainage* 70 (3): 490–504.

Kumar, P., A. Mishra, N.S. Raghuwanshi, and R. Singh. 2002. “Application of unsteady flow hydraulic-model to a large and complex irrigation system.” *Agricultural Water Management* 54 (1): 49-66.

Muema, F.M., P.G. Home, and J.M. Raude. 2018. “Application of benchmarking and principal component analysis in measuring performance of public irrigation schemes in Kenya.” *Agriculture* 8 (10): 162–167.

Muema, F.M. 2018. “Comparative performance evaluation of public rice irrigation schemes in Western Kenya using benchmarking process.” PhD dissertation, JKUAT-PAUSTI, Nairobi.

Nam, W.H., E.M. Hong, and J.Y. Choi. 2016. “Assessment of water delivery efficiency in irrigation canals using performance indicators.” *Irrigation Science* 34 (2): 129–143.

Onyango, A.O. 2014. “Exploring options for improving rice production to reduce hunger and poverty in Kenya.” *World Environment* 4 (4): 172–179.

Patel, D.P., J.A. Ramirez, P.K. Srivastava, M.K. Bray, and D.E. Han. 2017. “Assessment of flood inundation mapping of Surat city by coupled 1D/2D hydrodynamic modeling: a case application of the new HEC-RAS 5.” *Natural Hazards* 89: 93–130.

Rose, N., S. Sankaranarayanan, S.K. Pande, and D. Das. 2019. “Application of FAO-CROPWAT software for modelling irrigation schedule of rice in Rwanda.” *Rwanda Journal of Agricultural Sciences* 1 (1): 7–13.

Serede, I.J., B.M. Mutua, and J.M. Raude. 2015. “Calibration of channel roughness coefficient for Thiba Main Canal Reach in Mwea Irrigation Scheme, Kenya.” *Hydrology* 3 (6): 55–65.

Too, G., J.K. Kollongei, J.O. Onyando, and S.A. Mulindi. 2019. “Analysis of Water Use in Rice Production under Paddy System and SRI in Ahero Irrigation Scheme, Kenya.” *Africa Environmental Review Journal* 3 (2): 190–198.

US Army Corps of Engineers (USACE). 2016. "HEC-RAS River Analysis System." *Hydraulic Reference Manual, Version 5.0*, G.W. Brunner (author), Hydraulic Engineering Centre, Davis, CA.