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A review for hydraulic analysis of irrigation canals using HEC-RAS model: A case study of Mwea irrigation scheme, Kenya

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Abstract: Hydraulic simulation models could be suitable tools for understanding the hydraulic characteristics of irrigation systems. In this study HEC-RAS model will be tested in terms of error estimation and used to determine canal capacity potential. Thiba main canal reach in Mwea Irrigation Scheme (MIS), approximately 100 Kilometers North East of Nairobi City was selected. MIS being a model scheme in the country, its contribution to food security and growth of the sector is inherent. Sluice gates and trapezoidal canals are amongst the structures in the Thiba main canal reach system. HEC-RAS model will be calibrated and validated using two sets of observed discharges, gate openings and water levels. Due to its minimal estimation errors, HEC-RAS model would be appropriate in evaluation of canal hydraulics steady state conditions to improve on scheme performance.

Keywords: HEC-RAS, Irrigation, Hydraulic, Canal Reach, Capacity, Discharge

1. Introduction

Water use and competition among different users has been growing at more than twice the rate of population increase over the last century, leading to often conflicts among them. For instance, water use for irrigation accounts for about 70% of all freshwater worldwide and irrigation has been ranked as one of the activities that utilize a large fraction of fresh water in many countries. Molden (2007) asserts that in the near future, less water will be available for agricultural production due to competition with other sectors. At the same time, food production will have to be increased to feed the growing world population estimated at 81 million persons annually (UN, 2013). It has been further estimated that the world will need to feed 1.5 to 2 billion extra people by 2025 (Rosegrant *et al*., 2002). With less water being available for irrigation and the ever increasing population, agricultural sector will be faced by serious challenges to produce more food with little water (FAO, 2011).

In Kenya, rice is ranked the third most important food crop after maize and wheat especially for the urban population (Keya, 2013). It is mainly irrigated by surface irrigation systems and water is distributed in basins by flooding the paddy fields since it is one of the heavy water consumers. With the dwindling availability of fresh water for irrigation, there is need to optimally utilize the resource. This can be achieved through several strategies that include; sustainable river catchment management, proper design of water canals, hydraulic structures and proper scheduling for release to farmers, operation and maintenance of the systems (Maghsoud *et al*., 2013). In addition to infrastructural improvement, further efforts have been developed to manage the limited available irrigation water like introduction of new rice for Africa (NERICA) varieties whose plant physiology requires little water to thrive. The use of System of Rice Intensification (SRI) which allows rice paddy to be grown in straight lines at a specified spacing leading to higher yields of rice is also another strategy.

Mathematical models have also been used to understand the hydraulic behaviour of complex and large irrigation networks especially for evaluation and improvement of system performance. Some of these irrigation models which have been tested and evaluated include; MODIS (by Delft University of technology), DUFLOW (by Delft University), CANAL (by Utah State University), CARIMA (Holly and Parrish, 1991), USM (Rodgers and Merkley, 1991), SIC (Cemagref, France), PROFILE (Delft Hydraulic, 1991), FLOP, Mike II (Danish Hydraulic Institute, 1995), DORC (HR Wallingford, 1992), SOBEK (Delft Hydraulic, 1994) and ODIRMO (Delft University of Technology, 1985).

These studies have been undertaken by Mutua and Malano (2001), Kumar *et al*.,2002, Mishra *et al*.,2001), Shahrokhnia *et al*., 2004, Wahl *et al*., 2011, Maghsoud *et al.*, 2013, Hicks and Peacock (2005) and ASCE Task Committee on Irrigation canal system Hydraulic Modeling (1993). It is more economical therefore to test and use the present models in comparison with developing new ones (Burt and Styles, 1999).

The steady state HEC-RAS model was developed by U.S. Army Corps of Engineers (2001) to perform one-dimensional hydraulic calculations for a full network of earth and constructed channels. This model works by solving water surface profiles through computation of energy equation balance from one cross section to the next using iterative steps known as the standard step method as per Figure 1.

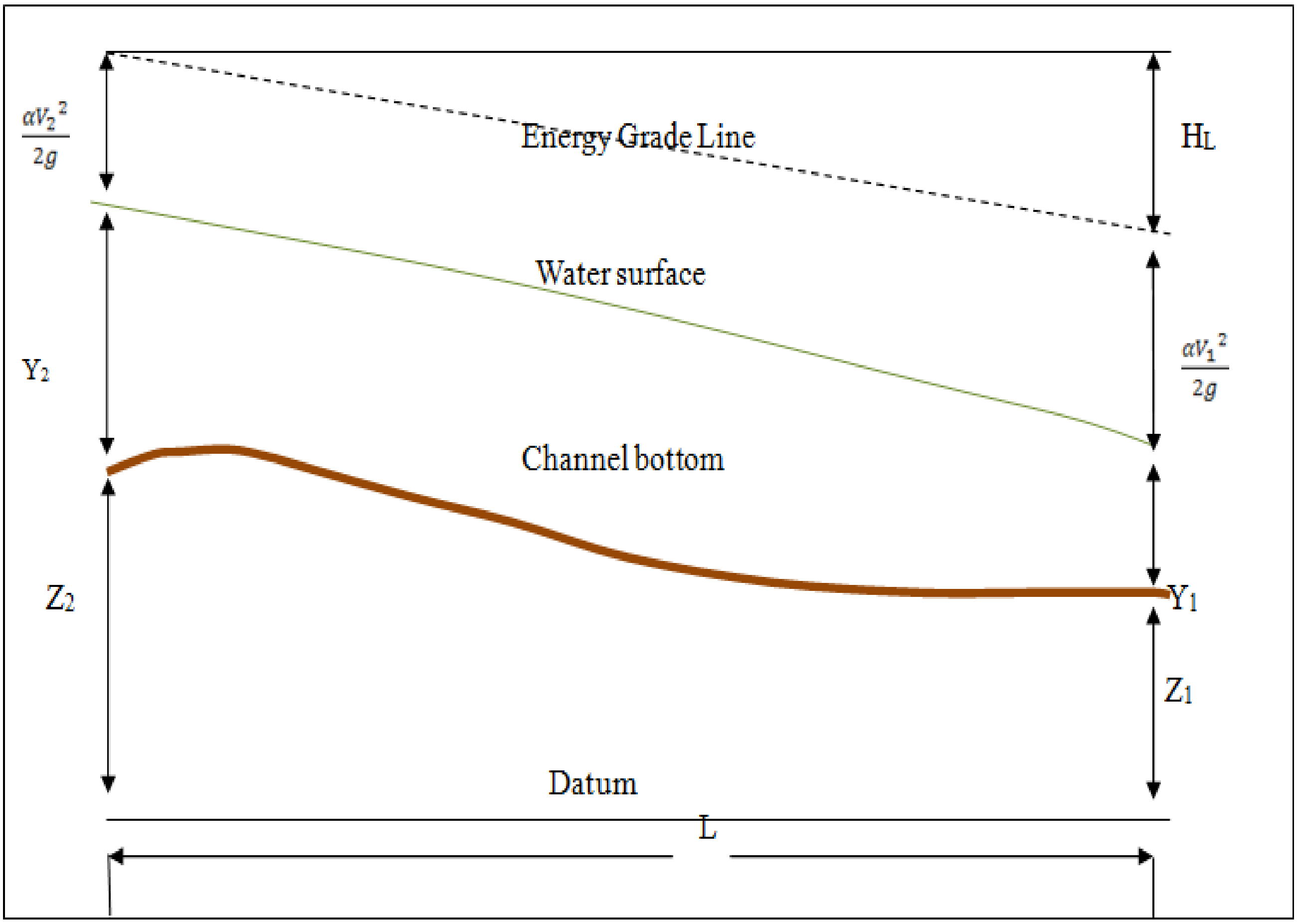

Figure 1. *Illustration of water surface profiles and energy lines between two points*

According to Nyagah (1990), MIS system has low irrigation efficiency and could not meet its intended benefits. He attributed this to poor design, construction and lack of maintenance. In addition, he noted that conveyance losses which occur in concrete canals in Kenya varied between 0.0026 and 0.0754 $l/s/m^2$.

MIS currently directs every effort to supply irrigation water to 9,080 ha by efficient use of limited water. This water was originally available for a command area of 6,600 ha only. This corresponds to an additional increase in water demand of 37.6 % (Koei, 1994). Over the last two decades, the out-growers whose farms were originally not part of the command area have developed their own land from 1,300 ha to 2,000 ha and yet, still rely on the MIS infrastructure.

In this study, the steady state HEC-RAS which is usually used for river flow analysis will be reviewed for its application to MIS.

2. Description of the Study Area

Mwea Irrigation Scheme is located in Kirinyaga South Sub-County, Kirinyaga County approximately 100 Kilometres North East of Nairobi. It lies on the Southern outskirts of Mt. Kenya and has a gazetted area of 30,350 acres. It is located between 1,100 m and 1,200 m above mean sea level (a. s. l.). The scheme stretches between latitudes 0° 37’S and 0° 45’S and between longitudes 37° 14’E and 37° 26’E as given in Figure 2.

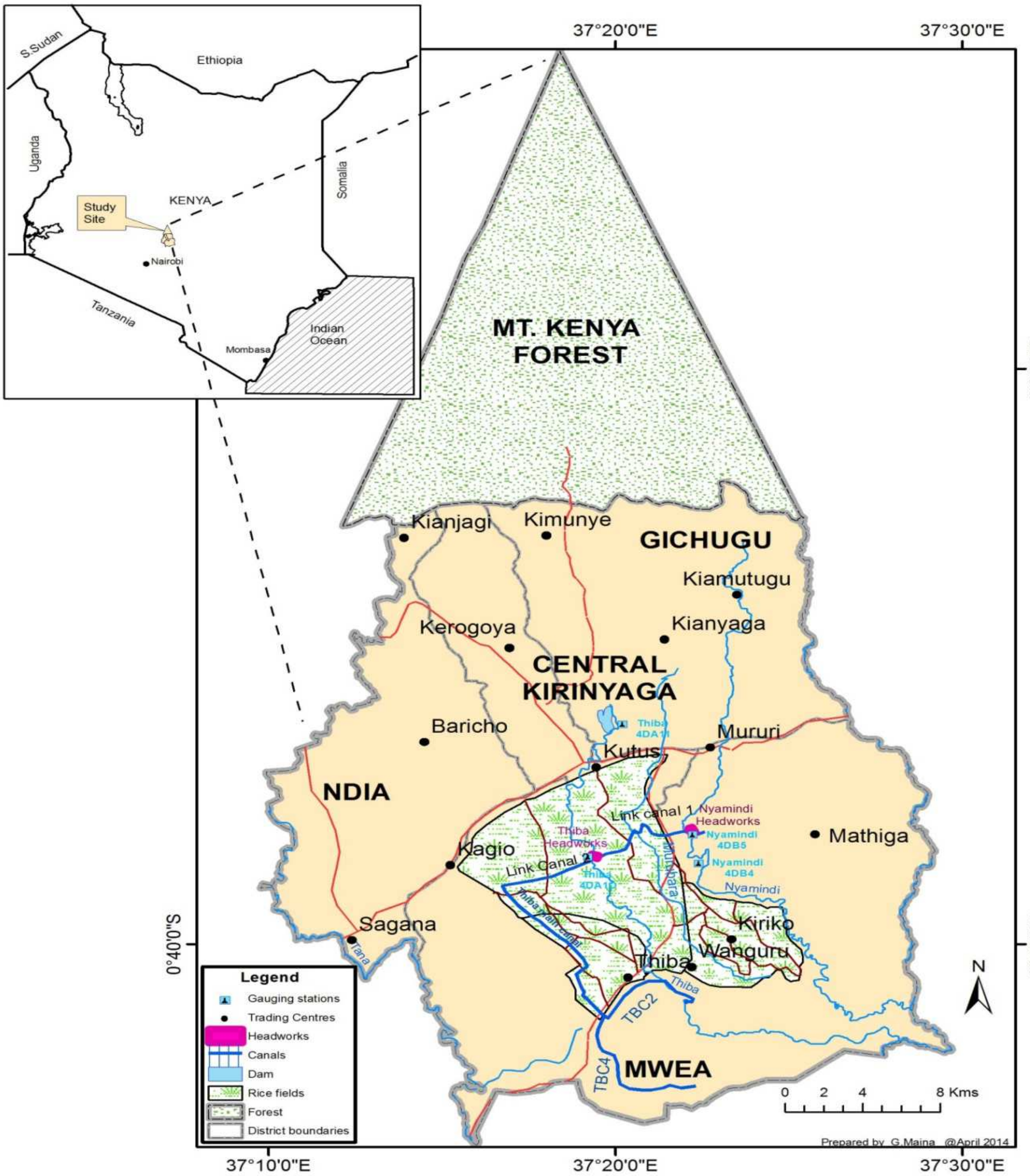

Figure 2. Map of Kenya showing Mwea irrigation Scheme

3. Principles of HEC-RAS Model and its Application

This will include reduction of the system into a layout drawing indicating all canals that withdraw water from the main infrastructure as illustrated in Figure 3. It will be developed using geometric data editor available in HEC-RAS (Hameed *et al.*, 2013). This will show discharge flow direction into or out of the system. Structures in the channel will be captured at this stage and a summary of their effect registered.

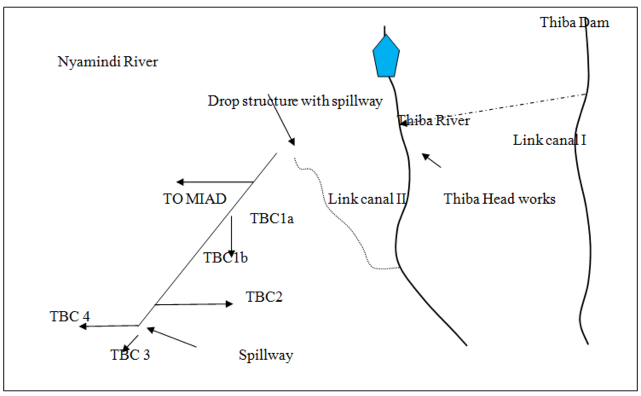

Figure 3. Schematic presentation of Thiba system

4. Fundamental Functions of the HEC-RAS Model

The energy equation is used to calculate the total head of water as the summation of the bed elevation, average flow depth and the velocity head at a cross section. Equation 1 illustrates the brief principle of water surface study in HEC-RAS model.

$$H = Z + y + \frac{\alpha v^2}{2g} \tag{1}$$

Where,
H = Total head of water (m)
α = Kinetic energy correlation coefficient
Z = Bed elevation at a cross section (m)
y = Flow depth at a cross section (m)
g = Acceleration of gravity (m^2/s)
ῡ = Average velocity (m/s)
Between two sections, Equation 1 becomes:

$$Z_A + y_A + \frac{\alpha v^2}{2g} = Z_A + y_A + \frac{\alpha v^2}{2g} + H_L \tag{2}$$

In open channels (USACE, 2001) the energy equation becomes:

$$(\partial A/\partial t)\,\Delta t \;=\; -V_m\;(\partial A/\partial L) - \;VA_m\;(\partial A/\partial L) \tag{3}$$

Where,
m = subscriptions for the mean values of V and A
L = Channel length (m)
t = Incremental time to be calculated

In canal simulation, channel roughness is a sensitive parameter in the development of hydraulic model (Timbadiya *et al*., 2011). Flow resistance equation used for friction losses are computation with a friction slope from Manning's equation. Flow resistance equation uses a form of these models to define an equation that applies average roughness to the wetted perimeter of a cross section (USACE, 2001a).

$$Q = K{S_f}^{1/2} \tag{4}$$

Where,
Q = Discharge (m^3/s)
K = Channel conveyance (m)
S_f = Friction slope (m/m)
Conveyance at a cross section is obtained by:

$$K = \frac{\Phi}{n}\,\mathrm{A}R^{2/3} = \frac{\Phi}{n}\,\mathrm{A}\left(\frac{A}{P}\right)^{2/3} \tag{5}$$

Where,
A = Cross-sectional area normal to the direction of flow (m^2)
Φ = Unit conversion (SI=1.000)
K = Channel conveyance (m)
n = Roughness coefficient
P= Wetted perimeter (m)
R = Hydraulic radius (m)

The cross-sectional area and wetted perimeter are a function of channel geometry. If the cross section is trapezoidal, then the equation is given as:

$$\mathrm{A} = \mathrm{y}\;(b + \;z y) \tag{6}$$

$$\mathrm{P} = \mathrm{b} + 2\mathrm{y}\;\left(\sqrt{z^2 + 1}\;\right) \tag{7}$$

Where,
A = Cross-sectional area normal to the direction of flow (m^2)
P = Wetted perimeter (m)
y = Flow depth at a cross section (m)
z = Side slope of the channel

Both primary and secondary data will be measured and reviewed respectively. Thiba system will be divided into two reaches; Link canal II and Thiba Main canal reach. Three boundary conditions will be selected, at the headworks, end of Link canal II and at end of Thiba Main canal. Upstream and downstream data that include discharge and design water levels will be collected. Number of cross-sections to be used on Link canal II and Thiba main canal will be determined by Samuels Equation (Pender *et al*., 2010).

$$D_X = 0.15\,{}^{D}\!/_{S} \tag{8}$$

Where,
D_X = Cross-section spacing
D = Bankful depth
S = Bed slope

Details about the cross-sections to be collected include; cross section number and chainage, bed slopes, side slopes, canal depth, elevations and the corresponding discharge at the cross section estimated using the Area-Velocity method.

$$Q = \sum_i^n q_i \;= \sum_{i=1}^n Va = \sum_{i=1}^n \frac{\left(V_{i-1} + V_i\right)}{2}\frac{\left(d_{i-1} + d_i\right)}{2}\left(b_i + b_{i+1}\right) \tag{9}$$

Where,
b_i = Horizontal distance of measuring point i from the bank of canal
n = Number of segments
d_i = Depth
V_i = Averages of mean velocities

5. Model Calibration and Validation

The model will be calibrated and validated using two sets of observed discharges, gate openings and water levels. The upstream and downstream boundary conditions will be measured using a rating curve at the end of the main canal and discharges at the source. During calibration, Manning's "n", discharge calibration factors and coefficients will be changed iteratively until the differences between simulated and observed values of discharges and water levels are small. The calibration procedure gives the actual Manning's of the canal and discharge coefficients of the gates. The accuracy of calibrated parameters will be tested using the differences between second set of observed data and the new simulated values. This will validate the model. The suitability of the model will be evaluated based on the differences between observed and simulated values.

6. Conclusion and Recommendations

In the study, new discharge equations will be obtained for the submerged rectangular gates using observed and measured data sets. Other equations will be used in HEC-RAS model for accurate simulations. HEC-RAS model will also be tested using observed data obtained from the Thiba Main Canal reach in MIS.

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