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Original Article

Application of HEC-RAS model for adaptive water allocation in a Large-Scale Rice Irrigation Scheme

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ABSTRACT

Water allocation is a key component of good water management in an irrigation system. Water imbalance between upstream and downstream has been a major issue at Tanjung-Karang Rice Irrigation Scheme Malaysia. This study applied the HEC-RAS model to estimate water for supply and analysed its allocation to the demand in the scheme. Water demand was computed based on water requirement, effective rainfall and seepage/percolation. Results of R^2, NSE, PBIAS and RSR during the model calibration and validation were 0.66, 0.64, 0.94 and 0.60; and 0.65, 0.59, 1.77 and 0.64, respectively. The irrigation scheme was under-supplied from January-March and over-supplied from April-June during the off-season. While in the main-season was under-supplied from July-September and over-supplied from October-December. Similarly, the excess water during the off and main seasons for the period was 40.10 and 52.40 Mm^3 respectively. Whiles the deficit water during the same seasons was 52.46 and 53.14 Mm^3, respectively. This suggests providing an adequate storage facility, which could store excess water during low water demand and use it in the period of water shortage. The developed model could therefore assist in estimating the over/under-supply with respect to the demand thereby storing the excess for use during the period of high demand.

1. Introduction

Effective and optimum agricultural production depend on the management of various natural resources surrounding the agricultural sector. Water is among the vital resources required for the agricultural production of any nation. The net productivity of crops depends on the proper utilization and management of this key resource. However, researchers have ascertained that the world is facing the crisis of such vital resource [1-3]. This crisis is not because of the physical scarcity of the water but is a result of poor management of its resources [4, 5]. Studies on global-scale water scarcity projections indicated that about two-thirds of the world's population are projected to fall within water-stressed areas by the year 2025 [6]. Many rivers in the world stop flowing and drying up with increasing intermittent flow because of climate change and anthropogenic effects [7, 8]. The water revalvery has increased in recent years to a stage of physical scarcity [9, 10]. This led to water imbalances in some irrigation schemes [11]. To achieve sustainable development, optimal allocation of limited water resources is needed for various purposes [12]. However, the optimum allocation of water to farms is a computationally complex issue due to many factors, including irrigation limitations and constraints [13]. Yield failure is often triggered by uncertainty in water

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supply or its shortages during the critical crop growth period [14]. Hence, the need for extensive care to the operation and management of these resources to overcome the water related problems.

Irrigated agriculture is estimated to cater for about 60% of future food requirements [15]. The largest portion of human accessible water withdrawal and water consumption from rivers, lakes and aquifers is used mostly for irrigation. The water use by irrigation has been estimated to reach about 2,500 km^3 $year^{-1}$ globally, and this represents almost 70% of total human water use [16]. In Malaysia, the irrigation sector has the greatest annual water withdrawals, with more than 80% of the country's water demands accounted for by rice irrigation use [17]. Irrigation is being criticized for wasting a lot of water due to poor performance and low efficiencies. The manual quantification and regulation of flow, especially in large irrigation schemes have been a challenge to irrigation system. Consequently, this led to inadequate delivery between supply and demand. For instance, there have been imbalances between water supply from the upstream and the water demand at the intake of the scheme [18].

Models have been very helpful in assessing irrigation water allocation capacities [19]. Various hydraulic models were developed and applied in different irrigation schemes to address various problems. For example, DUFLOW (*Dutch Flow)*, MODIS (Modelling Drainage and Irrigation Systems) and CARIMA (*Calcul des Rivieres Mailles)* models were respectively evaluated by Clemmens [20], Schuurmans [21], and Rogers and Merkley [22]. MIKE 11 and MIKE SHE models were applied by Singh [20]. Kumar [21] used a crop-based irrigation operation (CBIO) model for secondary canal scheduling/rotation. However, the complexity of some of these models has been a major setback, which consequently affects their performance [22, 23]. A tracer analysis was applied to calculate hydraulic and hydrodynamic characteristics of rivers with a velocity range from 0.108 m/s to 1.93 m/s [24]. The Hydrologic Engineering Centers River Analysis System (HEC-RAS) is a software for flow simulation, which has advantage of generating river geometry using spatial data with the Geographic Information System (GIS) component of the model, Hydrologic Engineering Centers Geo River Analysis System (HEC-GeoRAS). This is very helpful in canals with data scarcity as in Malaysia, where the agricultural catchments are poorly gauged [22]. However, research on the hydraulic modelling of an irrigation system using the HEC-RAS model is very limited [25]. Recently, the model was incorporated for simulation of water allocation in an irrigation scheme [10]. Therefore, this study applied the HEC-RAS model to model the river discharge for adequate water allocation at Tanjung Karang Rice Irrigation Scheme (TAKRIS) Malaysia. The software is applicable in a wide range of geographic areas for solving the widest possible range of problems including large river basin water supply, studies of water availability, urban drainage, flow forecasting, and future urbanization impact [26-30]. Others include, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation [31-33]. The goal was to compute and highlight the hydraulic characteristic parameters of the river system, estimate the available water for supply and analyse its allocation with respect to the water demand by the scheme. This could address the problems of water wastage in irrigation systems, water shortage in period of higher crop water demand and in flood control, thereby improving the water allocation.

2. Materials and Methods

2.1. Study area

Tanjung Karang Rice Irrigation Scheme (TAKRIS) is located at latitude $3^0\ 25^/$ to $3^0\ 45^/$ N and longitude $100^0\ 58^/$ to $101^0\ 15^/$ E in Malaysia as shown in Figure 1.

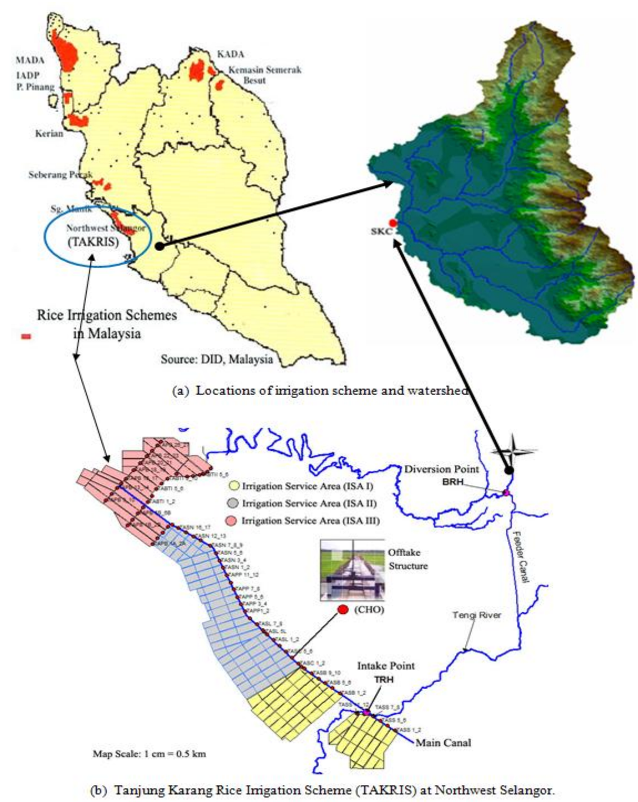


Fig 1. Tanjung Karang Rice Irrigation Scheme. Adopted from Ismail et al [10].

The runoff of the Upper Bernam river basin is the main source of irrigation water for the scheme [17, 34]. The diversion of water for irrigation is from the Basin at the Bernam River Headworks (BRH), situated about 130 km upstream from the estuary of the Bernam River, and it reaches the scheme at Tengi River Headworks (TRH) through a feeder canal [35, 36]. The annual water surface evaporation is about 1,600 mm. The mean monthly temperature is 28°C, with a daily variation of 8°C, and the mean monthly humidity is 77% [36].

2.2. Hydraulic modelling of the river

Hydraulic modelling has been extensively used in hydraulic analysis and water flow simulation in a river or channel. The HEC-RAS model is one of the most accurate and widely applied models in river analysis system [37-40] and was adopted in the present study. The HEC-RAS 5.0 version 2016 with Geospatial Hydrologic Modelling Extension (Arc-Hydro and HEC-GeoRAS) was used which is available for public domain from the HEC website www.hec.usace.army.mil. The software comprises four one-dimensional hydraulic components for steady flow computations; unsteady flow simulation; transport computations of movable boundary sediment and water quality analysis, using a common geometric data representation and common geometric and hydraulic computation routines. This paper focused on the unsteady flow component of HEC-RAS to perform and analyze flow parameters of the Bernam-Tengi River.

2.3. Input data and model setup

The aim of the HEC-RAS Model is to compute water-surface elevations at different sections of interest using routing hydrographs through the system. The data needed to perform these computations are categorized into two; geometric data and flow data. Figure 2 summarized the model setup for the scheme. A 30 m x 30 m Digital Elevation Model (DEM) raster of the study area was used to establish the river system connectivity; cross-section data reach length, etc., using HEC-GeoRAS. The overall cross-section traits of the channel were extracted and finally exported into the HEC-RAS model.

The river reach was divided into 59 cross-sections, perpendicular to the flow direction from the upstream to downstream sections of the river. The cross-sections were numbered from 1, corresponding to TRH (downstream) to 59, corresponding to the Bernam watershed outlet (Figure 3).

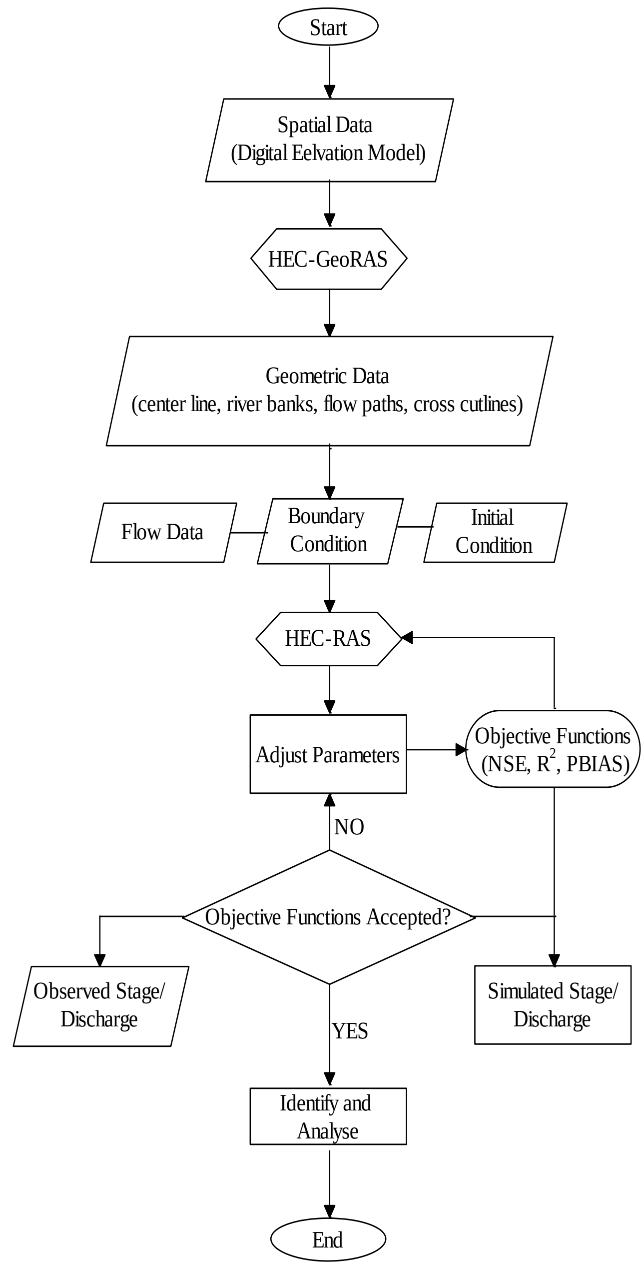
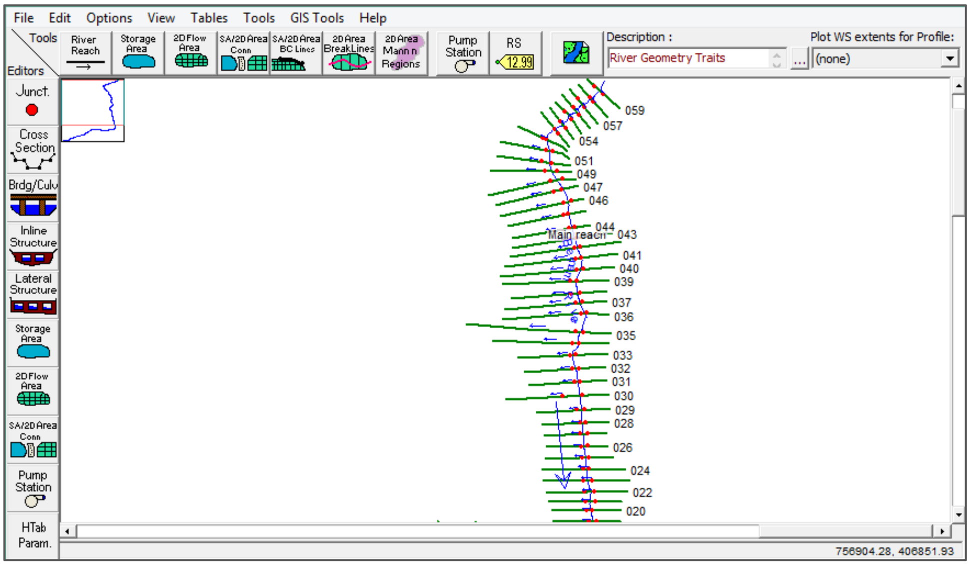
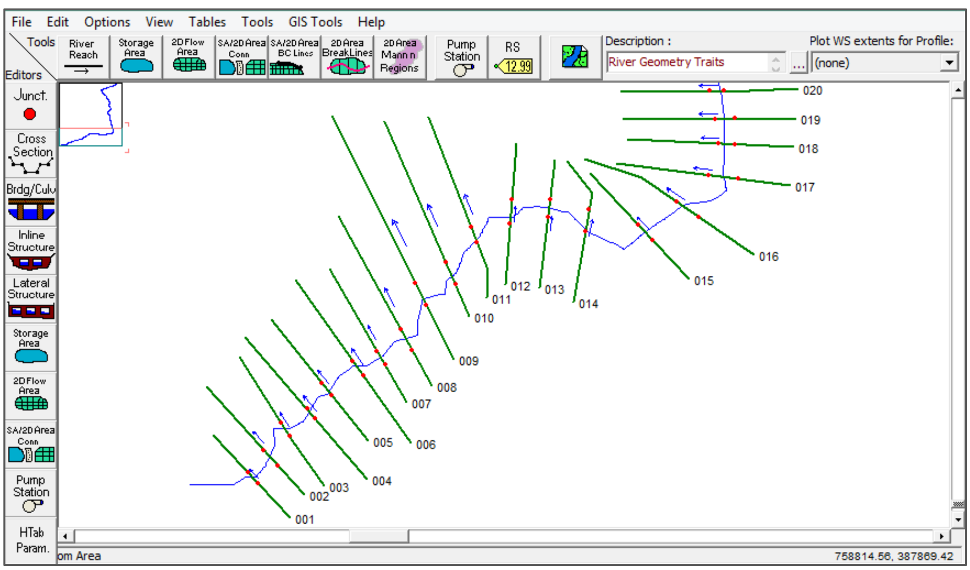


Fig 2. HEC-RAS model setup [10]



(a)



(b)

Fig 3. River geometry traits at the study location [10]: (a) cross-sections at Bernam river/feeder canal; (b) cross-sections at Tengi river.

The upstream of the river was routed with a flow hydrograph at the river gauging station. The flow data was initially simulated using the HEC-HMS model. The downstream of the river was routed with the flow hydrograph at the TRH.

2.4. Flow characteristic calculation

Discharge values at the outlet of the watershed (obtained using HEC-HMS); flow regime and boundaries conditions were specified to perform the routing. Subsequently, the flow characteristics including hydrographs, hydraulic properties tables, etc., were computed at various reaches and sections of the river.

2.5. HEC-RAS calibration and validation

The most sensitive calibration parameter required by the HEC-RAS model is channel resistance; specifically, Manning's coefficient (n). Its values can be extracted with the aid of a land-use map of the area using HEC-GeoRAS. However, due to insufficient land use data, covering all the river area, previously presented n values were used as first estimate of the appropriate channel resistance and adjusted through calibration [41]. Because of irregular and limited flow data in the area, reliable data for four years (from 2001 to 2004) was used for model evaluation. Finally, the calibrated model was validated using the 2004 daily discharge records. The model's performance was assessed using the most widely used statistical measures (i) Coefficient of Determination, R^2, (ii) Nash-Sutcliffe Efficiency NSE, (iii) Percentage bias PBIAS, (iv) Root mean square error–standard deviation ratio (RSR).

2.6. Irrigation water demand

Daily irrigation water demand for the command area was calculated based on the crop water requirement, effective rainfall and seepage/percolation as expressed in equations 1 and 2:

$$IR_t = (ET_{c,t} - ER_t + SP_t + RP_t); \quad \text{if } RP_t < WD_{max} \tag{1}$$

$$IR_t = 0; \quad \text{if } RP_t > WD_{max} \tag{2}$$

Where;

IR_t = rice irrigation requirement on t^{th} day (mmday^{-1}),
$ET_{c,t}$ = rice water requirement on t^{th} day (mmday^{-1}),
ER_t = effective rainfall on t^{th} day (mmday^{-1}) and
SP_t = seepage/percolation losses in the rice field (mmday^{-1}).
A maximum water demand (WD_{max}) of 100 mm is usually the standard practice during the normal irrigation supply in Malaysia
RP_t = required ponding water depth on the day.
A reference evapotranspiration-(ET_o)-crop factor (K_c) technique was used to determine the crop ET_c (mm day^{-1}) as expressed in equation 3. The K_c values reported by Chan and Cheong [42] for Malaysia rice variety were used.

$$ET_c = ET_o \times K_c \tag{3}$$

The ET_o (mm day^{-1}) was determined using FAO-56 Penman-Monteith (PM) Model, as given by Allen et al [43]:

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

Where;

ET_o = standardized reference crop evapotranspiration for short grass (mm d^{-1}),
R_n = Net radiation at crop surface (MJ m^{-2} day^{-1}),
G = Soil heat flux density (MJ m^{-2} day^{-1}),
T = air temperature at 2 m height (°C),
u_2 = wind speed at 2 m height (m sec^{-1}),
e_s-e_a = saturation vapour pressure deficit (kPa),
Δ = slope vapour pressure curve (kPa °C^{-1}),
γ = Psychrometric constant (kPa °C^{-1}) and 900 is a constant factor.
Effective rainfall (ER) was derived from rainfall (RF) within the period of simulation., as expressed in equations 5 and 6

$$ER = 0.6RF, \quad \text{for } RF < 200 \text{ mm/month} \tag{5}$$

$$ER = 0.3(RF + 200), \quad \text{for } RF \geq 200 \text{ mm/month} \tag{6}$$

3. Results and Discussion

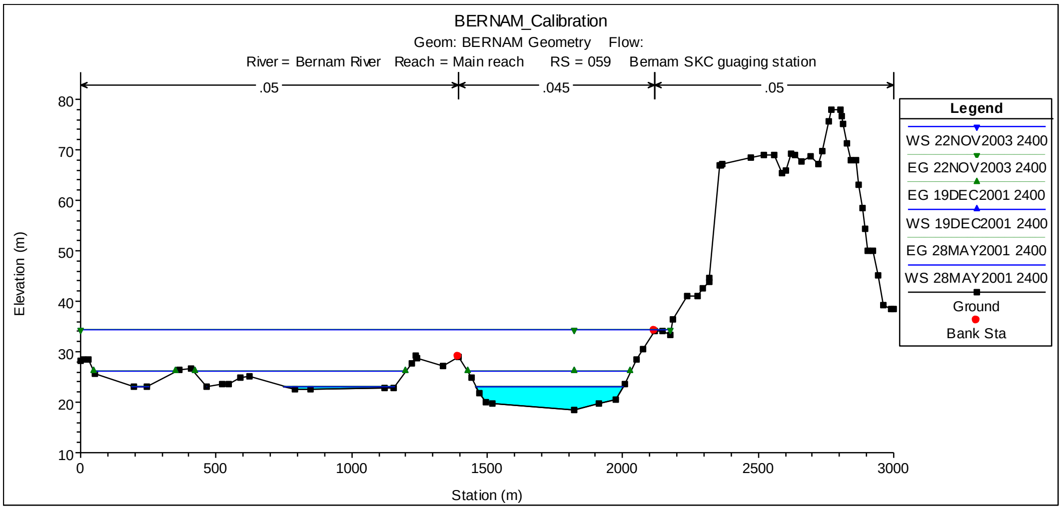
3.1. Calibration and validation of HEC-RAS model

The results of model evaluation show that the simulation is satisfactory since the values are greater than 0.5 [44]. The R^2, NSE, PBIAS and RSR during the calibration and validation periods were 0.66, 0.64, 0.94 and 0.60; and 0.65, 0.59, 1.77 and 0.64, respectively. However, an underestimation of simulated flow was observed by the model. Nevertheless, the model was able to optimally capture low and peak flows for most of the days.

3.2. Wetted sections

There are different characteristics of the wetted sections at different river sections, for a given discharge specified the upstream of the river. For instance, the wetted sections at the upstream (section 59), the TRH (section 1) and RS58 varied for a given discharge as depicted in Figure 4. The wetted section is wider at the upstream and narrow at TRH and cross-section 58. Moreover, the initial elevation of the sections determines their water surface levels at a given discharge from the upstream. In addition, for RS1 at TRH (downstream), the flow is emanated in both the main channel and the floodway, because of its position (initial elevation) and the narrow shape. However, for RS58 and upstream, the flow is completely channelled to downstream section. The amount of a given flow at the upstream also determines the extent of the floodway, with large volume spilling out of the channel for a large inflow. For example, a large discharge of 79.7 m^3/s released at the upstream on 22 November 2003 extended in almost all the floodways in all the three sections. Conversely, some portion of the possible flood areas was flooded at a medium discharge of 58.2 m^3/s on 19 December 2001 in the (4) same sections. In addition, the lower flow of 28.1 m^3/s on 28 May 2001 released from the upstream was completely channelled except for the section downstream (TRH), where it extended to some portion of the floodways. These results show that with the increase of roughness coefficient and pattern of topography, the water level profile is no longer uniform and appears as a gradual variable.

Considering the river, being a water source to the irrigation scheme, the farm plots located downstream might be flooded, particularly during the wet-season. The depth of flow changes with season, with maximum during monsoon and minimum in post-monsoon [45].The wetted section of river was also found decreasing from upstream to downstream by other studies [27, 45]. Similarly, during the off-season, the downstream might experience water shortage because the wetted section is narrow, which is associated with over spilling of flow. The scheme often experience water shortage as reported by Ismail et al [10]. This could be due to this characteristics effect. This suggests for a proper cropping pattern and the selection of crop type to be cultivated at the downstream section.



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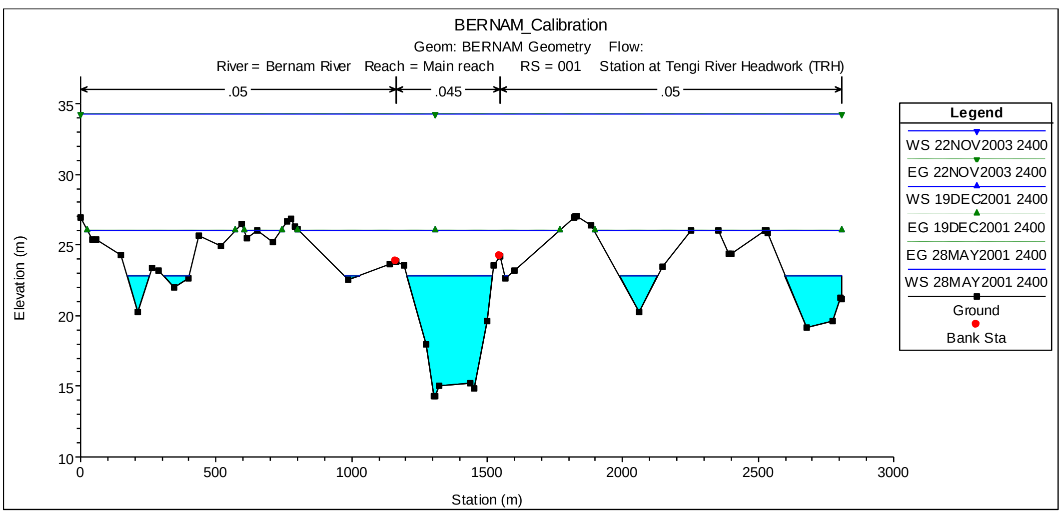

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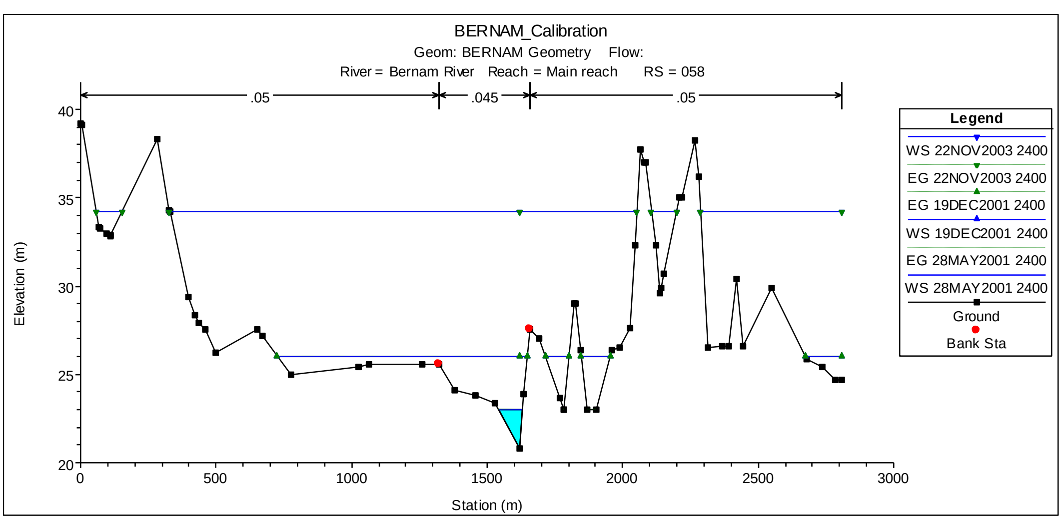

(c)

Fig 4. (a) wetted section at SKC; (b) wetted section at TRH; (c) wetted section at RS58.

3.3. Velocity Profile

Figure 5 shows the distribution of flow velocity along the river for various discharges, specified at the upstream. The velocities are lower in almost all the sections along the river. This is associated with the nature of the slopes along the river. In these sections, free surface slopes, stream power and shear total are lower. The highest velocity is observed at cross-section 58 (at about 47 km from downstream section). In this section, free surface slopes, stream power and shear total are more important and flow area is smaller too. Moreover, the velocities vary with the discharge amount. For instance, the large discharge amount of 74.9 m^3/s on 29 November 2001 reported an upper-velocity trend followed by 57.9 m^3/s on 30 December 2003. The lower trend was attained at a discharge of 28 m^3/s on 14 August 2003. These results revealed that the river along the irrigation scheme is affected by the fluctuations of water level profile. Although velocity profiles decrease at the downstream as also reported by other studies [27, 45], however, the variations of velocity flow explicitly depend on the channel characteristics such as topography of the river bed, channel roughness, etc.

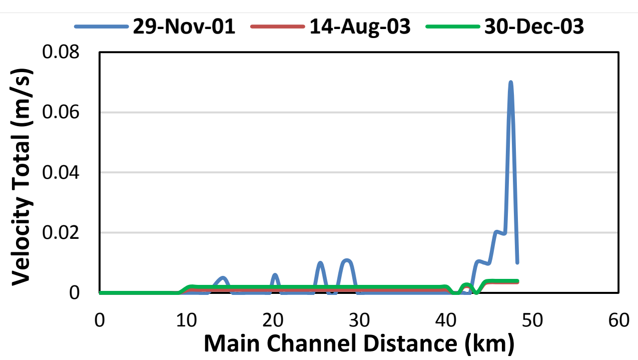

Fig 5. Flow velocities distribution at Bernam/Tengi river.

3.4. Flow Area

Figure 6 shows the distributions of flow areas for various discharges specified upstream. The flow area varies greatly at different sections of the river and increases with discharge. Noticeably, the discharge of 65.7 m^3/s on 04 November 2004 has a larger flow area across all the sections along the river followed by 52.4 m^3/s on 04 May 2004. The least flow area is at 31.9 m^3/s on 05 February 2004. The highest flow area along the river is at cross-section 35 (this section corresponds to the highest wetted perimeter) followed by cross-section 9. The former corresponds to a confluence, where water is diverted from the Bernam River to the feeder canal at BRH whilst the latter is a section just downstream to where the feeder canal is connected to the Tengi River. Moreover, the flow areas along the feeder canal section are relatively small with almost similar level compared to other sections along the Bernam and Tengi rivers, respectively. The flow area changes according to Manning's roughness coefficient effect. Consequently, this could lead to a decrease in the capacity of the river. This result shows that flow areas increase with the increase in discharge at upstream, however, the roughness coefficient affect its capacity [27]. Similarly, Ghadai et al [45] reported increase in the area of flow when discharge at upstream is increased.

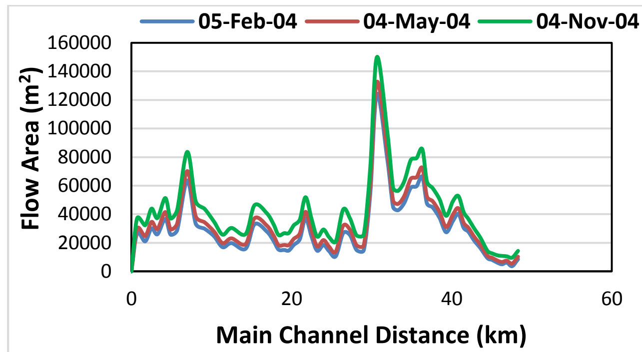

Fig 6. Flow area distributions at Bernam/Tengi river.

3.5. Volume

Figure 7 shows the cumulated volume along the river system for various discharges. It can be observed that the volume increases with discharge along the various sections of the river. For instance, there is a higher volume for a discharge of 79.5 m^3/s on 13 November 2001 followed by 37.7 m^3/s on 05 September 2001. The least volume was on 01 August 2001, for a discharge of 28.7 m^3/s. Moreover, for given streamflow, the volume decreases slowly from upstream to downstream when the inflow is relatively low and with a high decrease rate for the higher inflow of 79.5 m^3/s. This could be due to the soil texture through its permeability, evaporation, and roughness coefficient effect. A similar increase in total volume within a river flow was reported by Traore et al [27]. This can negatively affect the water availability downstream for irrigation activities at the Scheme.

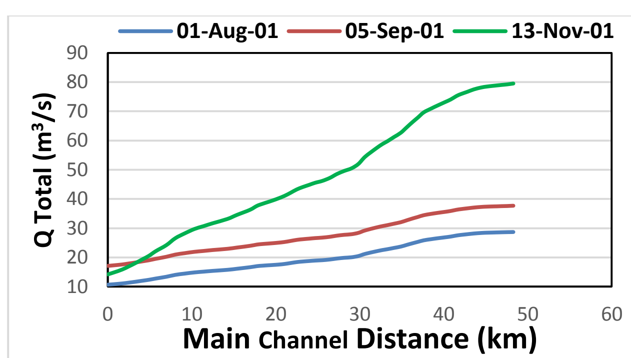

Fig 7. Total volume profiles at Bernam/Tengi river.

3.6. Matching water demand and supply

The daily water demand (needed supply) by the scheme was computed and compared with the actual supply modelled using the HEC-RAS model. The upstream water supply to the scheme is not managed based on the amount of water required. As a result, the simulated supply to the scheme fluctuates over the seasons, with over-supply in certain periods and under-supply in others in relation to the irrigation scheme required supply as shown in Figure 8. Water supply systems should maintain a balance between supply and demand in order to be effective in water management. This balance is achieved through operational actions, many of which include the use of predictive models [46]. This implies that a developed hydraulic model for the system would improve water allocation by ensuring the right supply of the desired needed water in the scheme, avoiding over-supply in low-demand periods and under-supply in high-demand periods.

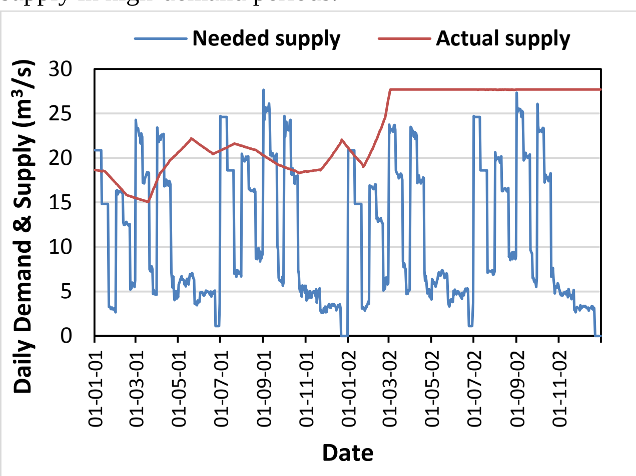

Figure 8. Daily water demand and supply in Tanjung Karang Rice Irrigation Scheme for 2001-2002.

The scheme is operated under two cropping seasons namely off-season (January to June) and main season (July to December). The validated HEC-RAS model was applied to predict the available water for supply to the scheme for 8 years (2010-2018) and this was compared with the estimated scheme's water demand during the same period. Figure 9 shows the monthly average excess and shortage irrigation amounts in the scheme. It is observed that there was a consistent improper balance between the scheme water demand and the available water for supply across the seasons. The scheme is under-supplied from January to March, and over-supplied from April to June during the off-season. Similarly, there is a shortage supply from July to September, as well as excess supply from October to December in the main-season. The excess water (which runs as waste) during the off and main-seasons for the period is 40.10 and 52.40 Mm^3, respectively. Whiles, the deficit water (shortage supply) during the off and main-seasons for the same period is 52.46 and 53.14 Mm^3, respectively. This suggests provision of adequate storage facility along the main canal, which can store excess water during low water demand and use it in the period of shortage.

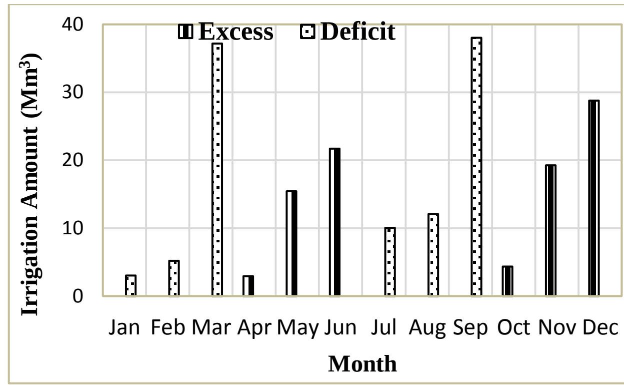

Fig 9. Monthly average excess and shortage irrigation amount in Tanjung Karang Rice Irrigation Scheme (2010-2018).

4. Conclusion

HEC-RAS Model was applied in this study for hydraulic analysis of the river in the area. The main flow characteristics along the study reach were computed using the model thereby locating the high, low, and constant flow characteristics areas, the large and narrow section areas. Certain parameters such as total surface area, volume, etc. were found decreasing from upstream to downstream. These results could be useful to the decision-makers for water allocation, water management, hydraulic structure implementation, environmental planning and flood control in the Bernam river basin. Water supplied to the scheme as simulated using the developed HEC-RAS was noticed to be improperly allocated compared to the needed supply, thereby wasting excess water in the period of low demand and shortage supply in the period of high demand. This suggests provision of a storage facility along the main canal of the scheme, which could be used to store water at a period of low demand and use it during the period of high demand. It is recommended that a general survey of the river should be conducted to generate another set of geometry to assess the accuracy of the data. A proper water allocation of the scheme should be scheduled based on the actual scheme water demand with the aid of the developed HEC-RAS model.

Conflict of Interest

The authors declare that they have no conflict of interest.

Abbreviation List

BRH	Bernam River Headworks
CARIMA	*Calcul des Rivieres Mailles*
CBIO	Crop Based Irrigation Operation
DEM	Digital Elevation Model
DUFLOW	*Dutch Flow*
ER	effective rainfall
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Centers Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Centers River Analysis System
HEC-GeoRAS	Hydrologic Engineering Centers Geo River Analysis System
IR	irrigation requirement
MIKE-SHE	*System Hydrologique Europeen*
MODIS	Modelling Drainage and Irrigation Systems
n	Manning's roughness coefficient
NSE	Nash-Sutcliffe Efficiency
PBIAS	Percentage bias
R^2	Coefficient of Determination
RP	required ponding water depth
RSR	Root mean square error–Standard deviation Ratio
SP	seepage/percolation losses in the rice field
TAKRIS	Tanjung Karang Rice Irrigation Scheme
TRH	Tengi River Headworks
WD_{max}	maximum water demand

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