Modeling water balance components and irrigation efficiencies in relation to water requirements for double-cropping systems

Md. Hazrat Ali a, Lee Teang Shui a,*, Kwok Chee Yan a, Aziz F. Eloubaidy a, K.C. Foong (Senior Engineer) b

a Faculty of Engineering, University Putra Malaysia, 43400 UPM, Serdang, Selangor Darul Ehsan, Malaysia
b Muda Agricultural Development Authority, Alor Setar, Kedah, Malaysia

Accepted 10 January 2000

Abstract

This paper describes the estimation of total water requirements as well as reservoir releases required to replenish the water deficit for double cropping of rice. A water balance equation is derived and the performance of a project is analyzed. The water balance components were modeled without calibration, and compared with measured data whenever possible. The potential evapotranspiration $ET_p$ were modeled for monthly time series using Penman–Monteith model [Monteith, J.L., 1965. Symp. Soc. Exp. Biol. 19, 205–234]. To estimate surface runoff, the proportion of elementary areas that are saturated were described by a spatial distribution function, considering the average total existing water (TEW) of both cropping seasons from 1991 to 1997. The monthly rainfalls (1971–1997) of 53 uniformly distributed rainfall stations were averaged and the rainfall considered uniform over the whole area. The effective meteorological input $M_e$ was considered positive to produce runoff. The variation of the soil suction head and hydraulic conductivity with moisture content, studied by Brooks and Corey [Brooks, R.H., Corey, A.T., 1964. Hydraulic properties of porous media. Hydrology Paper No. 3, Colorado State University, Fort Collins, CO] was applied in the Green–Ampt model [Green, W.H., Ampt, G.A., 1911. J. Agric. Sci. 4 (1), 1–24] to estimate infiltration.

The performance of a farm irrigation system is, in general, evaluated by the efficiency of the system. The nonlinear Muskingum–Cunge method [Cunge, J.A., 1969. J. Hydraulics Res., Int. Assoc. Hydraulics Res. 7 (2), 205–230] was applied as a distributed channel routing technique to calculate the conveyance losses from the study reservoir (Pedu Reservoir) to the end of the main canal, a total reach of about 108 km. The mean conveyance efficiency from the Pedu dam to the Pelubang barrage (67 km reach) was found to be 66%, while the same from the Pedu dam to the end of the main canals was found to be 59%. Using Central Canal Right Bank Drain (CCRBD) A1
block data as reported by Batumalai and Nassir [Batumalai, R., Nassir, M.A., 1986. Effective water utilization with on farm terminal infrastructure. Northern Regional Water Seminar, Alor Setar, Malaysia], the distribution efficiency was determined to be 94%. The water use efficiency was estimated using MADA’s field water supply data. The overall project efficiency for the main and off-seasons were calculated separately and found to be 18 and 32%, respectively. The total water requirements for rice in the main and off-seasons were determined and the amounts of water needed to release from the reservoir to meet the crop water deficit for double cropping were estimated to be 1385 million cubic meters (MCM).

**Keywords:** Water balance model; Channel routing; Irrigation efficiencies; Water requirements; Reservoir release

1. Introduction

The Muda Irrigation Project (Fig. 1) covers a total area of 126 000 ha, out of which about 97 000 ha is under the double cultivation of paddy rice (Muda Agricultural Development Authority, MADA, 1977). It is the largest double cropping area in Malaysia. The area is located at about 5°45′–6°30′N latitude and 100°10′–100°30′E longitude in the vast flat alluvial Kedah-Perlis Plain which is 20 km wide and 65 km in length, between the foothills of the Central Range and the Straits of Malacca. The area is generally flat with slopes of 1 in 5000 to 1 in 10 000 ranging from +4.5 m in elevation in the inland fringe to +1.5 m in elevation in the coastal area (MADA, 1977).

Evapotranspiration involves a highly complex set of processes, which are influenced by many local factors such as precipitation, soil moisture condition, plant water requirements, and the physical nature of the land cover (Dunn and Makay, 1995). Climatic conditions, which determine both the scale and the temporal distribution of
watershed hydrology, may attenuate or accentuate evapotranspiration. In the Muda area, Malaysia, it is found from the measured data (1971–1997) that the mean annual actual evaporation can account for 67% of the mean annual precipitation. Thus, a good estimate of evaporation and evapotranspiration is required if water sustainability is to be achieved. Measurements of evapotranspiration are rarely available. In the absence of measurements, an alternative approach is to use mathematical models to predict the variations in evapotranspiration, giving meteorological data to describe variations in the climate. The present study employs the Penman–Monteith potential evapotranspiration model (Monteith, 1965), to estimate ETp and the Penman equation to estimate the free-surface or potential evaporation $E_p$.

After flowing across the watershed surface, excess rainfall becomes direct runoff at the watershed outlet under the assumption of Hortonian overland flow (Horton, 1933). For practical estimation of rainfall excess or storm runoff volume, numerical representations or models are required of rainfall and losses or of the relation of runoff to rainfall. In this paper, the ARNO rainfall-runoff model (Todini, 1996), which has widespread application in catchment hydrology, is considered. The major advantage of this model is the fact that it is entirely driven by the total catchment soil moisture storage, which is functionally related, by means of simple analytical expressions, to the dynamic contributing areas, and to the drainage and the percolation amounts (Todini, 1996).

In this study, the Green–Ampt infiltration model (Green and Ampt, 1911) which has widespread application as an approximate theory-based infiltration model is considered. The model, though approximate, provides analytical solutions to the flow fields. The variation of the suction head and hydraulic conductivity with moisture content studied by Brooks and Corey (1964) was incorporated in the present model. To apply the Green–Ampt model, the effective hydraulic conductivity of the soil $K$, the wetting front suction head $\psi$, the porosity $\eta$ and the effective porosity $\theta_e$, need to be measured or estimated.

Farm irrigation systems are designed and operated to supply the individual irrigation requirements of each field on the farm while controlling deep percolation, runoff, evaporation, and operational losses. The performance of a farm irrigation system is determined by the efficiency with which water is diverted, conveyed, applied and by the adequacy and uniformity of application in each field on the farm. The purpose of the efficiency concepts is to show where improvements can be made that will result in more efficient irrigation. When evaluating the performance of a farm irrigation system, it is often useful to examine the efficiency of each system component. This allows components that are not performing well to be identified.

The scheme is highly dependent on rainfall, fulfilling about 51% of the irrigation requirements. Two dams (Pedu and Muda) contribute about 29%, while the uncontrolled river flow and recycling supply contribute about 15 and 5%, respectively. In fact, the reservoirs were so depleted that irrigation for the 1978 dry season crop was impossible, and again in 1983 and 1984, only half of the area could be irrigated (Kitamura, 1990). The shortage of reservoir water remains the most serious constraints on the establishment of stable double cropping of rice.

Thus, the aims of this paper can be summarized as: (i) to simulate model $E_p$ with the observed pan evaporation; (ii) to use the calculated $E_p$ in ETp estimation; (iii) to estimate
the surface runoff from the whole project area; (iv) to estimate seepage and percolation; (v) to estimate the conveyance efficiency, water use efficiency, water distribution efficiency, and overall project efficiency; and (vi) to calculate the total water requirements for stable double cropping of rice.

2. Modeling approach

The water balance components considered in the model are shown in Eq. (1). The inflow to the field consists of the total water supplied through precipitation and irrigation, and the outflow consists of water leaving the field through evapotranspiration, surface runoff, seepage, and percolation. In Eq. (1), the potential evapotranspiration \( \text{ET}_p \) is used, because the actual evapotranspiration \( \text{ET}_a \) that can disappear due to stomata resistance of the canopies, is assumed to coincide with the potential evapotranspiration. The field storage is considered to be sufficiently represented by the ponded surface water and the soil moisture is constant during the crop growth period. The water balance equation for a single paddy plot can be expressed as

\[
W(t + \Delta t) = W(t) + P(t, t + \Delta t) - \text{ET}_p(t, t + \Delta t) - R(t, t + \Delta t) - I(t, t + \Delta t) \\
- S_l(t, t + \Delta t) + \text{IR}(t, t + \Delta t)
\]

where \( W(t + \Delta t) \) is the soil moisture content at time \( t + \Delta t \), \( W(t) \) the soil moisture content at time \( t \), \( P(t, t + \Delta t) \) the area precipitation between \( t \) and \( t + \Delta t \), \( \text{ET}_p(t, t + \Delta t) \) the loss through potential evapotranspiration between \( t \) and \( t + \Delta t \), \( R(t, t + \Delta t) \) the runoff between \( t \) and \( t + \Delta t \), \( I(t, t + \Delta t) \) the percolation loss to groundwater between \( t \) and \( t + \Delta t \), \( S_l(t, t + \Delta t) \) the seepage loss between \( t \) and \( t + \Delta t \), and \( \text{IR}(t, t + \Delta t) \) the irrigation supplied between \( t \) and \( t + \Delta t \). In Muda Irrigation Scheme, irrigation is generally supplied from three major sources. Thus, the term \( \text{IR}(t, t + \Delta t) \) can be extended as \( \text{IR}_R + \text{IR}_{UCF} + \text{IR}_{Rec} \) where \( \text{IR}_R \), \( \text{IR}_{UCF} \), \( \text{IR}_{Rec} \) represent the amount of water supply from the reservoirs, uncontrolled river flow, and recycled drainage water, respectively. All the quantities representing averages over the Muda area are expressed in millimeters. The uncontrolled flow means the water supply by the runoff from the catchment area and the direct precipitation falling on the river systems downstream of the Pedu dam. This supply is a vital source to minimize the water shortage for double cropping of rice in the area.

2.1. Potential evapotranspiration

Gangopadhyaya et al. (1966) defined potential evapotranspiration as the combined process of transpiration by vegetation and evaporation from the saturated bare soil. Estimating potential evapotranspiration \( \text{ET}_p \) is more difficult than estimating \( E_p \) because several vegetation-species-specific model parameters are required. The only process based model that is widely used, and that accounts for the influence of vegetation on the evapotranspiration regime, is the Penman–Monteith energy formula (Monteith, 1965).
The Penman–Monteith potential evapotranspiration model (Monteith, 1965) is

\[
ET_p = \frac{\Delta(R_n - G) + (\rho_a C_p [e^0(z) - e_d(z)]/r_a)}{\lambda(\Delta + \gamma[1 + (r_s/r_a)])}
\]  

(2)

where \(ET_p\) is the potential evapotranspiration (mm per day); \(\lambda\) the latent heat of vaporization of water (MJ kg\(^{-1}\)); \(\Delta\) the gradient of the saturation-vapor-pressure-temperature function (kPa °C\(^{-1}\)); \(R_n\) the net radiation (MJ m\(^{-2}\) per day); \(G\) the soil heat flux (MJ m\(^{-2}\) per day); \(\rho_a\) the air density (kg m\(^{-3}\)); \(C_p\) the specific heat of the air at constant pressure \(\hat{=} 1.013\) kJ kg\(^{-1}\) K\(^{-1}\); \(e^0(z)\) the saturated vapor pressure of the air (kPa), a function of air temperature measured at height \(z\); \(e_d(z)\) the mean actual vapor pressure of the air measured at height \(z\) (kPa); \(r_a\) the aerodynamic resistance to water-vapor diffusion into the atmospheric boundary layer (s m\(^{-1}\)); \(\gamma\) the psychrometric constant (kPa °C\(^{-1}\)); and \(r_s\) the vegetation canopy resistance to water-vapor transfer (s m\(^{-1}\)).

One of the limitations of the Penman–Monteith equation is its data requirements. At a minimum, the model requires air temperature, wind speed, solar radiation, and the saturation-vapor-pressure deficit.

The net radiation \(R_n\) of Eq. (2) can be obtained \((R_s, R_{nl}\) by Penman, 1948) as

\[
R_n = R_s - R_{nl}
\]

(3)

where \(R_s\) (MJ m\(^{-2}\) per day) is the short-wave solar radiation, \(R_{nl}\) (MJ m\(^{-2}\) per day) net longwave outgoing radiation, \(T_a\) the air temperature in K (i.e. temperature in °C+273), \(\alpha\) the surface reflectivity or albedo, whose recommended values are 0.08 for open water surfaces and 0.23 for most crop covered surfaces (Maidment, 1993); and \(\sigma\) the Stefan–Boltzmann constant \(\hat{=} 4.903 \times 10^{-9}\) MJ m\(^{-2}\) K\(^{-4}\) per day.

The effective soil depth to which heat is transferred is greater for longer temperature cycles. To estimate the change in soil heat content for daily temperature fluctuations °C (effective soil depth typically 0.18 m), the soil heat flux \(G\) (MJ m\(^{-2}\) per day) can be computed (Wyjik van and de Vries, 1963) by

\[
G = 0.38(T_{Day2} - T_{Day1})
\]

(4)

The rate of water vapor transfer away from the ground by turbulent diffusion is controlled by aerodynamic resistance \(r_a\) (sm\(^{-1}\)) and can be estimated (Thom and Oliver, 1977) from

\[
r_a = \frac{4.72[\ln(z/z_0)]^2}{1 + 0.536U_2^2}
\]

(5)

where \(z\) is the height at which meteorological variables are measured (m); \(z_0\) is the aerodynamic roughness of the surface (0.00137 m) for a standardized measurement height for wind speed, temperature, and humidity measurements of 2 m (Thom and Oliver, 1977); and \(U_2\) is the average wind speed at 2 m height (m s\(^{-1}\)).

The stomatal resistance of the whole canopy, referred to as the surface resistance \(r_s\), is less when more leaves are present since there are then more stomata through which
transpired water vapor can diffuse. One approximation (Allen, 1986) for $r_s$ is

$$r_s = \frac{200}{L}$$

(6)

If $h_c$ is the mean height of the crop, then the leaf area index $L$ can be estimated (Allen et al., 1989) by

$$L = 24h_c \quad \text{(clipped grass with } 0.05 < h_c < 0.15 \text{ m})$$

$$L = 5.5 + 1.5 \ln(h_c) \quad \text{(alfalfa with } 0.10 < h_c < 0.50 \text{ m})$$

(7)

Since potential evaporation occurs from an extensive free water surface, it follows that the canopy resistance $r_s = 0$ is the appropriate value of surface resistance for estimating potential evaporation from Eq. (2) (Fennessey and Kirshen, 1994). This is the well-known Penman equation (Penman, 1948).

### 2.2. Surface runoff

A sub-basin of given surface area $S_T$ (excluding the surface extent of water bodies such as reservoirs or lakes) is, in general, formed by a mixture of pervious and less pervious areas, the response to precipitation of which will be substantially different. For this reason, the total area $S_T$ is divided into impervious area $S_I$ and pervious area $S_P$.

The ARNO Rainfall–Runoff Model (Todini, 1996) is

$$R = M_e + \frac{S_T - S_I}{S_T} \left\{ (W_m - W) - W_m \left[ (1 - (W/W_m))^{1/(b+1)} - \frac{M_e}{W_m(b+1)} \right]^{b+1} \right\}$$

for $0 < M_e < (b+1)W_m \left(1 - \frac{W}{W_m}\right)^{1/(b+1)}$

(8)

and

$$R = M_e + \frac{S_T - S_I}{S_T} (W_m - W) \quad \text{for } M_e \geq (b+1)W_m \left(1 - \frac{W}{W_m}\right)^{1/(b+1)}$$

(9)

where $R$ is the surface runoff (mm); $M_e$ is the effective meteorological input (mm), defined as the difference between precipitation and potential evapotranspiration, and considered positive to produce runoff; $W$ is the catchment average amount of soil moisture content (mm); $W_m$ is the catchment average soil moisture content at saturation (mm); and $b$ is the soil moisture curve parameter, which expresses the degree of homogeneity of soil characteristics, should generally be between 0.1 and 0.01.

The catchment average amount of soil moisture content $W$ can be evaluated as

$$W = w_m \left[ 1 - (1 - x)^{(b+1)/b} - \frac{b}{b+1} + \frac{b}{b+1} (1 - x)^{(b+1)/b} \right]$$

$$= \frac{w_m b}{b+1} \left[ 1 - (1 - x)^{(b+1)/b} \right]$$

(10)

where $x$ is the fraction of pervious area ($0 < x < 1$) at saturation, $w$ is the elementary area soil
moisture at saturation (mm), and $w_m$ is the maximum possible soil moisture content in any elementary area of the catchment (mm).

If all the pervious area has reached saturation, i.e. $x=1$, Eq. (10) becomes

$$W = W_m = \frac{w_m}{b + 1}$$

(11)

The relationship between the average and the elementary area soil-moisture storage quantities can be found as:

$$w = (b + 1)W_m \left[1 - \left(1 - \frac{W}{W_m}\right)^{1/(b+1)}\right]$$

(12)

In this model, an interception component (Rutter et al., 1971, 1975) is not explicitly included. If the precipitation $P$ (mm) is larger than the potential evapotranspiration $ET_p$, the actual evapotranspiration $ET_a$, assuming that the stomata resistance of the canopies will not be affected, is considered to coincide with the potential evapotranspiration.

2.3. Infiltration

The Green–Ampt model is an approximate theory-based infiltration model utilizing Darcy’s law. Water is assumed to infiltrate into the soil as piston flow resulting in a sharply defined wetting front, which separates the wetted and unwetted zones.

The infiltration rate $f$ according to the Darcy’s law can be approximated by

$$f = K \left[\frac{\psi \Delta \theta + F}{F}\right]$$

(13)

where $K$ is the hydraulic conductivity of the soil, $\psi$ is the soil suction head, $F$ is the cumulative infiltration, and $\Delta \theta$ is the change in moisture content. Since $f = \frac{dF}{dt}$, Eq. (13) can be expressed as a differential equation in the one unknown $F$ to obtain

$$F(t) - \psi \Delta \theta \ln \left(1 + \frac{F(t)}{\psi \Delta \theta}\right) = Kt$$

(14)

Eq. (14) is the Green–Ampt equation for cumulative infiltration. Once $F$ is found from Eq. (14), the infiltration rate $f$ can be obtained from Eq. (13) or

$$f(t) = K \left(\frac{\psi \Delta \theta}{F(t)} + 1\right)$$

(15)

After laboratory tests of many soils, Brooks and Corey (1964) concluded that $\psi$ can be expressed as a logarithmic function of an effective saturation, $s_e$. If the residual moisture content of the soil after it has been thoroughly drained is denoted by $\theta_r$, the effective saturation $s_e$ is given by

$$s_e = \frac{w - \theta_r}{\eta - \theta_r}$$

(16)
where \( \eta \) is the soil porosity (total volume occupied by pores per unit volume of soil). The effective saturation has the range \( 0 \leq s_e \leq 1.0 \), provided \( \theta_e \leq w \leq \eta \). The change in the moisture content can be computed by

\[
\Delta \theta = (1 - s_e) \theta_e
\]

where \( \theta_e \) is the effective porosity. The soil porosity is computed from bulk density and particle density (normally assumed to be equal to 2.65 g cm\(^{-3}\)) as follows:

\[
\eta = 1 - \frac{BD}{PD}
\]

where BD is the soil bulk density (g cm\(^{-3}\)), and PD is the particle density (g cm\(^{-3}\)). If the cation-exchange capacity (CEC) of the clay, which is an indicator of the shrink-swell capacity of the clay, is available, the bulk density at the water content for 33 kPa tension can be estimated (Rawls, 1983) as

\[
BD = 1.51 + 0.0025(S) - 0.0013(S)(OM) - 0.0006(C)(OM) - 0.0048(C)(CEC)
\]

where \( S \) is the percent sand, \( C \) the percent clay, OM the percent organic matter \((1.7 \times \text{percent organic carbon})\), and CEC the ratio of cation-exchange capacity of clay to percent clay, which ranges from 0.1 to 0.9.

The Green–Ampt wetting front suction parameter, \( \psi \) can be estimated (Rawls and Brakensiek, 1983) as

\[
\psi = \exp \left[ 6.53 - 7.326\eta + 0.00158C^2 + 3.809\eta^2 + 0.0003445S - 0.04989S\eta \\
+ 0.0016S^2\eta^2 + 0.0016C^2\eta^2 - 0.0000136S^2C - 0.00348C^2\eta - 0.000799S^2\eta \right]
\]

2.4. Seepage

Seepage \( S \) refers to the horizontal movement (lateral flow) of water through the surrounding embankments from the irrigated area. High seepage loss leads to an increasing demand on irrigation supply and is undesirable. In this study, seepage is considered negligible in such a flat area.

2.5. Distributed channel flow routing

The modified Muskingum method, known as the Muskingum–Cunge method, (Cunge, 1969), is most effectively used as a distributed flow routing technique. The recursive equation applicable to each \( \Delta x_i \) subreach for each \( \Delta t^j \) time step is

\[
Q_{i+1}^{j+1} = C_1 Q_{i}^{j+1} + C_2 Q_{i}^{j} + C_3 Q_{i+1}^{j} + C_4
\]

which is similar to the Muskingum method, but expanded to include lateral inflow effects \( C_4 \) and the superscripts \( j \) and \( j+1 \) denote the times separated by the interval \( \Delta t^j \). The coefficients \( C_1, C_2, \) and \( C_3 \) are positive values whose sum must equal unity. The last term,
$C_4$ of Eq. (21) accounts for the effect of time $\Delta t$ and space $\Delta x$ averaged lateral inflow $\overline{q_i}$, i.e.

$$C_4 = \frac{\overline{q_i} \Delta x \Delta t}{2K_s(1 - X) + \Delta t}$$

where $K_s$ is a storage constant having dimension of time; and $X$ is a weighting factor expressing the relative importance of inflow and outflow ($0 \leq X \leq 0.5$).

For minimal numerical errors associated with the solution scheme, the space step $\Delta x$ should be selected as follows:

$$\Delta x \approx 0.5c \Delta t \left[ 1 + \left( 1 + 1.5 \frac{q}{c^2S_0 \Delta t} \right)^{1/2} \right]$$

(22)

where $c$ is the kinematic wave velocity ($\text{m s}^{-1}$), and $S_0$ is the bottom slope.

2.6. Efficiency

The overall efficiency of a farm irrigation system is defined as the percent of water supplied to the farm that is beneficially used for irrigation on the farm by the crop. The design of the irrigation system, the degree of land preparation, skill and care of the irrigator, are the principal factors influencing irrigation efficiency.

2.6.1. Water conveyance efficiency ($E_c$)

This term is expressed as percentage by the following equation:

$$E_c = 100 \left( \frac{Q^{j+1}}{I^j} \right)$$

(23)

where $Q^{j+1}$ is the discharge of water delivered by conveyance system to the field (outflow), and $I^j$ the inflow of water diverted from the source to the conveyance system (inflow).

2.6.2. Water use efficiency ($E_u$)

Water use efficiency can be computed for each field of the entire farm by the following equation:

$$E_u = 100 \left( \frac{\mathbb{V}_{nt}}{\mathbb{V}_a} \right)$$

(24)

where $\mathbb{V}_{nt}$ is the net volume of crop water requirement on day $t$, and $\mathbb{V}_a$ the volume of water applied in an area.

The daily water requirements by rice in the field are the difference between the sum of evapotranspiration, seepage and percolation losses, surface runoff and water needed to raise the ponding depth from the available storage to the desirable level. This can be expressed by a mass balance equation as

$$\mathbb{V}_{nt} = (ET_{pt} + L_t + S_{lt} + PD_t + R_t - P_t - WD_{t-1}) \times \text{(Irrigated area)}$$

(25)
where PD is the required ponding depth (mm). The subscripts \( t \) and \( t-1 \) represent time, day and previous day, respectively.

2.6.3. **Uniformity coefficient or water distribution efficiency (\( E_d \))**

The formula for water-distribution efficiency, which evaluates the extent to which water is uniformly distributed, is shown here:

\[
E_d = 100 \left( 1 - \frac{\bar{y}}{\bar{d}} \right)
\]

(26)

where \( y \) is the average of the absolute values of deviations from the mean (mm), and \( \bar{d} \) is the mean depth of water stored during the irrigation (mm).

Generally, the overall system efficiency \( E_i \) is the product of these efficiencies and can be expressed as

\[
E_i = \left( \frac{E_c}{100} \right) \left( \frac{E_a}{100} \right) \left( \frac{E_d}{100} \right) (100)
\]

(27)

### 3. Results and discussion

The developed water balance model is able to determine the water requirements of crops at a specific time period and the irrigation efficiency model was developed to test the performance of the project. The model components are to be compared with data collected from Muda Agricultural Development Authority, Malaysia, whenever possible. The analysis of the model outputs is presented and discussed separately in the following sections.

#### 3.1. Potential evapotranspiration

Long-term monthly averaged daily values of the estimated free-surface evaporation were compared with the mean monthly USBR Class A Black Pan evaporation (1971–1997) of 30 available stations, uniformly distributed in the area. The monthly averaged daily values of temperature, wind speed, possible sunshine and relative humidity meteorological data (1980–1997), which were all used as input variables to the \( E_p \) model, were taken from Station 27 (Kepala Batas, latitude: 06°12’N, and longitude: 100°24’E), as it is the only viable meteorological station exists in the project. The mean monthly general weather conditions at Kepala Batas are shown in Fig. 2. The extra-terrestrial radiation \( R_a \) (mm per day) was taken from the literature (Michael, 1978) and multiplied by the latent heat of vaporization of water \( \lambda \) (MJ kg\(^{-1}\)) to convert to \( R_a \) (MJ m\(^{-2}\) per day) for fulfilling the model requirements.

Fig. 3 shows that the long-term monthly averaged daily estimates of \( E_p \) for different months simulate more than 95% with the observed pan evaporation. The surface resistance \( r_s \) of the crop, assuming seasonal average crop height of 0.2 m, was incorporated in \( ET_p \) estimation instead of using crop coefficient \( K_c \). The surface
resistance is less when more leaves are present since there are then more stomata through which transpired water vapor can diffuse.

3.2. Surface runoff

The long-term (1971–1997) monthly averaged observed rainfall of 53 available stations and the model ET_p were used as the main inputs in surface runoff estimation. The area input to the runoff model was extracted from Geographical Information System (GIS) digitized map. The observed total existing water (TEW) from 1991–1997 in each infinitesimal area for dry (February–July) and wet (August–January) crop seasons was converted to moisture content (%) and averaged. Kitamura (1987) calculated TEW, considering a soil depth of 1 m, prior to 1 month of presaturation of the soil and found
that the TEW at 85 mm corresponded to 100% saturation of the soil up to 1 m depth. A very large value for the soil moisture curve shape parameter (i.e. $b>1$) will produce peak runoff responses event when the soil is mostly dry, and a large value for $W_m$ can reduce the outflow by a factor of 100% (Todini, 1996). The probable maximum soil moisture content $W_m$ is 85 mm, thus $b=0.01$ was considered to keep the model $W_m$ close to 85 mm. A higher value of $b$ than 0.01 will decrease $W_m$. The results show that no surface runoff is produced in the months of December–April (i.e. $M_e<0$), a peak value of 164 mm is achieved in September, and the average runoff (May–November) is 33% of the total rainfall occurred in the corresponding months (Fig. 3). The model runoff is not compared with the observed runoff because of non-availability of measured data.

3.3. Infiltration/percolation and seepage

The Green–Ampt equations used are for homogeneous soils and uniform land cover. These can be extended to describe infiltration into layered soils, when the hydraulic conductivity of the successive layers is known. As reported by Paramananthan (1989), the physio-chemical properties of subsoils of the Muda plain for Chengai soil series type are: 62% clay, 27% silt, 0.3% carbon, 0.05% nitrogen, 10.7% sand, and 0.28 CEC. Using these properties, the porosity and soil suction head were obtained. The soil porosity and the suction head were calculated using physio-chemical properties of the soil. Since the effective porosity of the study soil is not available, an effective porosity of 0.38 for the clay soil was considered (Rawls et al., 1983). The soil in the Muda area is a heavy clay (Chengai series), having coefficient of permeability $1 \times 10^{-7}$ to $8 \times 10^{-6}$ cm s$^{-1}$ (Kitamura, 1990). A permeability value of $1 \times 10^{-6}$ cm s$^{-1}$ was used in infiltration estimation and a mean daily infiltration rate of 1 mm per day was found. It is also found that the annual infiltration is 18% of the mean annual rainfall occurred in the area. The mean daily infiltration rate was determined by taking the daily infiltration rate for each month and averaged. The comparison between the observed mean monthly rainfall and calculated monthly infiltration is shown in Fig. 3. The seepage was neglected for such type of flat topography. Thus, the computed combined seepage and percolation loss for the Muda area can be regarded as equivalent to 1 mm per day, which is equivalent to the approximated seepage and percolation loss of 1 mm per day of MADA. (MADA, 1977). The model drainage (surface runoff) including seepage and infiltration loss is found to be 51%, while the same is 44% as reported by Kitamura (1990).

3.4. Soil moisture condition

The field moisture contents in different districts for main season and off-season from 1991 through 1997 were computed and compared as shown in Figs. 4 and 5. It is seen that the dry season average soil moisture content for Districts 2, 3, and 4 is the lowest in 1992, reaches a peak value in 1994 and thereafter decreases until 1996, whereas the moisture content for District 1 increases and reaches a peak value in 1994, and thereafter decreases. Although, the moisture content for all districts seemed to increase again after 1996, the 1998 dry spell in Malaysia might reduce its increment, indicating more water requirements for presaturation in near future during the off-season crop.
No significant change is noticed for the wet season’s average soil moisture content until 1995. After 1995, there occurred rapid reductions in soil moisture content for all the districts, indicating more water requirements during presaturation. It can be noted that the rainfall amounts showed in Figs. 4 and 5 are the mean monthly rainfalls occurred in the presaturation months only and thus, different from the rainfall shown in Fig. 3.

3.5. Efficiency

Nonlinear Muskingum–Cunge method was applied to calculate the conveyance losses from the Pedu dam to the end of the main canal, a total reach of about 108 km. The effect of lateral flow (inflow and/or outflow) was not considered because of non-availability of data. In this method, an estimated value of the unknown flow $Q_i^{t+1}$ and its corresponding $y_i$ value were used to compute $K_s$ and $X$. The solution–procedure is iterative and converges when computed and assumed values of $Q_i^{t+1}$ agree within a suitably small tolerance.
The conveyance efficiency was estimated for a range of Pedu discharge from 141.58 m$^3$ s$^{-1}$ (5000 ft$^3$ s$^{-1}$) to 7.08 m$^3$ s$^{-1}$ (250 ft$^3$ s$^{-1}$), which are the probable maximum and minimum limits of Pedu releases. The mean conveyance efficiency from the Pedu dam to the Pelubang barrage, a stretch of about 67 km, was found to be 67%, and the same from the Pedu dam to the end of the Central and Northern canals was found to be 59%. The time of arrival of water for 112.65 m$^3$ s$^{-1}$ (4000 ft$^3$ s$^{-1}$) discharge from the Pedu dam to the end of the northern canal was found to be about 19 h. Since no cross-sectional data is available for the lateral canals, the MADA’s calculated lateral conveyance efficiency of 80% was considered throughout the irrigated area.

Using CCRBD (central canal right-bank drain) A1 block data as reported by Batumalai and Nassir (1986), the distribution efficiency was found to be 94%. The $E_d$ as determined for the project case (with tertiary canal development) of the study area is equal to 81% (Batumalai and Nassir, 1986). Bos and Nugtren (1982) estimated $E_d$ as 95% for an average farm size of 0.85 ha with basin and continuous supply.

The water use efficiency $E_u$ was estimated using MADA’s field water supply data. Unusual values of $E_u$ (i.e. 0 and even more than 100%) were found while using MADA’s water supply data. The higher (i.e. greater than 80%) $E_u$ values were considered 80%, as the maximum limiting value of $E_u$ could be as high as 80% reported by Odhiambo and Murty (1996). Finally, the overall project efficiency for the main-season and off-season, were found to be 18 and 32%, respectively, which are higher than the 16% reported by Batumalai and Nassir (1986). Bos and Nugtren (1982) reported the project efficiency to be 24%. It is interesting to mention that none of them considered the conveyance loss from Pedu dam to Pelubang barrage.

### 3.6. Crop water requirements

Kitamura (1990) performed the water balance study for three dry seasons and two wet seasons (1984 dry season to 1986 dry season), using both experimental and observed data. He found that the average annual consumptive use of water for paddy cultivation was 2813 mm, out of which 1567 mm or 56% was for ET and 1246 mm or 44% was for DR (drainage including seepage and percolation). On the other hand, the average annual water supply was 2777 mm of which 908 mm or 33% were supplied by irrigation and 1869 mm or 67% by rainfall. The deficit of 36 mm between supply and consumption was accounted for TEW.

The designed water requirement is 2200 mm for two crops in a normal year as quoted in the Muda I feasibility report by the project consultants (Sir William Halcrow and Partners, 1964). Kitamura (1990) found that the observed water consumption was 30% more than that reported in the Muda I feasibility report. The water requirement was especially high for presaturation and for supplementary supply in the off-season (dry season). Such high presaturation and supplementary requirements in the off-season are due to the delay of field activities, such as land preparation, transplanting and direct seeding. The consumptive use of water was designed to be 8.6 mm per day for the dry season crop and 6.7 mm per day for the wet season crop (MADA, 1977).

The mean (1987–1997) model total water requirements for two crops in a year (i.e. for dry and wet seasons) were found to be 2314 mm (2232 million cubic meters (MCM)), out
of which 1323 mm or 1275 MCM (57%) is fulfilled by rainfall. While the uncontrolled river flow and recycled water were found to contribute 414 mm or 399 MCM (18%) and 69 mm or 67 MCM (3%). The reservoir supply was found to contribute 508 mm or 490 MCM (22%). The average irrigated area is 96 428 ha and the project efficiency, considering $E_u$ at 80%, is found to be 35%. To replenish the shortage of water requirements by double-cropping system, a total of 1436 mm (i.e. $508/0.35 = 1451$ mm) or 1385 MCM is needed to supply from the reservoir that accounts for the project efficiency. The authors found that the model water requirements for two crops is only 5% higher than that mentioned in the Muda I feasibility report and 18% lower than that obtained by Kitamura (1990).

4. Conclusions

Methods used to calculate the water balance components without model calibration were described. The model results were compared with observed data whenever possible. The overall project efficiency for the main and off-seasons were also obtained and compared. The overall efficiency shows that the project has low irrigation performance. The mean (1987–1997) model total water requirements for dry and wet seasons (i.e. for two crops in a year) were found to be 2314 mm (2232 MCM), out of which 1323 mm or 1275 MCM (57%) is fulfilled by rainfall. While the uncontrolled river flow and recycled water contributes 414 mm or 399 MCM (18%) and 69 mm or 67 MCM (3%). The authors found that the model water requirements for two crops is only 5% higher than that mentioned in the Muda I feasibility report and 18% lower than that obtained by Kitamura (1990). Incorporating the project efficiency, the authors found that the mean amount of water required to deliver from the reservoir for fulfilling the deficit of water requirements for double cropping is 1385 MCM.

Acknowledgements

The research described in this paper is supported by funds provided by the Intensification of Research in Priority Areas Program (IRPA), Ministry of Science, Technology, and Environment, Malaysia. The authors gratefully acknowledge the staff of Muda Agricultural Development Authority, Kedah, Malaysia, for their assistance in providing necessary unpublished data.

References


