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Geospatial Water Productivity Index (WPI) for Rice

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ABSTRACT

A GIS-based user-interface programme was developed to compute the geospatial Water Productivity Index (WPI) of a river-fed rice irrigation scheme in Northwest Selangor, Malaysia. The spatial analysis includes irrigation blocks with sizes ranging from 20 to 300 ha. The amount of daily water use for each irrigation block was determined using irrigation delivery model and stored in the database for both main season (August to December) and off season (February to May). After cut-off of the irrigation supply, a sub-module was used to compute the total water use including rainfall for each irrigation block. The rice yield data for both seasons were obtained from DOA (Department of Agriculture, Malaysia) of the scheme. Then, the Water Productivity Index (WPI) was computed for each irrigation block and spatial thematic map was also generated. ArcObjects and Visual Basic Application (VBA) programming languages were used to structure user-interface in the ArcGIS software. The WPI, expressed in terms of crop yield per unit amount of water used (irrigation and effective rainfall), ranged from 0.02 to 0.57 kg/m^3 in the main season and 0.02 to 0.40 in off season among irrigation blocks, respectively. The development of the overall system and the procedure are illustrated using the data obtained from the study area. The approach could be used to depict the gaps between the existing and appropriate water management practices. Suitable interventions could be made to fill the gaps and enhance water use efficiency at the field level and also help in saving irrigation water through remedial measures in the season. The approach could be useful for irrigation managers to rectify and enhance decision-making in both the management and operation of the next irrigation season.

Keywords: Water productivity index, spatial variability, Rice, GIS User-interface

INTRODUCTION

Rice irrigation is the largest water-consuming sector in Malaysia, and it faces competing demands from other sectors including industrial and domestic sectors. About 70% of the available surface water resources are

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consumed mostly for rice production (MOA, 2008). Due to the rapidly growing population and the competition for water in different sectors, it is imperative that the available water resources for irrigation supplies are used efficiently. A saving of 5% in irrigation water can meet 15% of water demand for the domestic and industrial sectors (Teh, 1998). A small improvement in water use for rice production would result in significant water savings for the other sectors. The present self-sufficiency level of rice production is 72% and the Government of Malaysia has targeted to achieve a self-sufficiency level of 100% by 2011. To achieve this goal, the development of arable lands for rice production and adequate irrigation supplies has to be ensured. Meanwhile, improving water productivity index through better utilization of available water resources is an option to divert the surplus irrigation water for other potential new rice growing areas. It is well known that Water Productivity Index (WPI) of rice irrigation schemes in Malaysia is low, which is usually less than 0.5. Thus, a systematic approach used to determine WPI is worthwhile to diagnose and rectify the water uses for rice production.

With the increasing population and limited water resources, the food security for future generations is at stake. In particular, the agricultural sector faces the challenge of producing more food with less water use by increasing Crop Water Productivity (Kijne *et al*., 2003). Thus, the application of water productivity analysis can provide clues for solutions to solve water management problems. Various methods for estimating water productivity at a range of scales, and for different agricultural systems were discussed by Cook *et al*. (2000). The analysis of water productivity is becoming increasingly important worldwide in light of population growth and increasing pressure on water resources (Abullaev & Molden, 2004). Water productivity analysis combines physical accounting of water with yield or economic output to give an indication of how much the value is obtained from the use of water (Molden & Shakthivadivel, 1999). In general, there are three types of crop water productivity that can be distinguished (Abullaev & Molden, 2004; Molden & Shakthivadivel, 1999; Immerzeel *et al*., 2008). A major constraint to increase food production is limited surface water availability (Aggarwal *et al*., 2000). Water productivity, a concept expressing the value or benefit derived from the use of water, includes various aspects of water management and is very relevant for arid and semi-arid regions (Kijne *et al*., 2003; Abullaev & Molden, 2004; Molden *et al*., 2001). WPI can be expressed in terms of grain yield per amount of water used.

Nowadays, proper utilization of available water resources for irrigation supplies and improvement of water productivity for irrigation schemes are the forefront issues due to the ever-increasing competition for water among the different sectors. A good irrigation depends on the ability for allocation of the available water at the proportional amount to the targeted irrigation service areas with respect to the water demands. Varying climates, soil and crop conditions, canal network, hydrological uncertainties, fluctuating flows in the river, unreliable water supply in the absence of a storage reservoir, and trade-off in water use by schemes have made the irrigation management difficult. Moreover, poor distribution of irrigation water at the tertiary level and the lack of proper monitoring of irrigation supplies have made difficult for spatial analysis of WPI. Therefore, the accounting of water use for rice irrigation is worthwhile to improve WPI for paddy farming.

Geospatial Information Systems (GIS) is an essential element for modern information techniques as it acts as the interface with the user. GIS, coupled with crop water simulation models, can be used as a powerful tool to analyze simple or complex spatial information in the irrigation scheme since the temporal and spatial dimensions could be studied at once. GIS is defined as a means of measuring spatial and attribute data into a computerized database system, thereby allowing input, storage, retrieval and analysis of geographically referenced data (Star & Estes, 1990). The GIS capabilities to integrate spatial data from different sources, with diverse formats, constitute the main characteristics of the system (Goodchild, 1993). This paper describes a systematic approach for the determination of geospatial Water Productivity Index (WPI), defined as the mass of production per unit water use in rice production, using field observations and water allocation simulation model.

Study Area

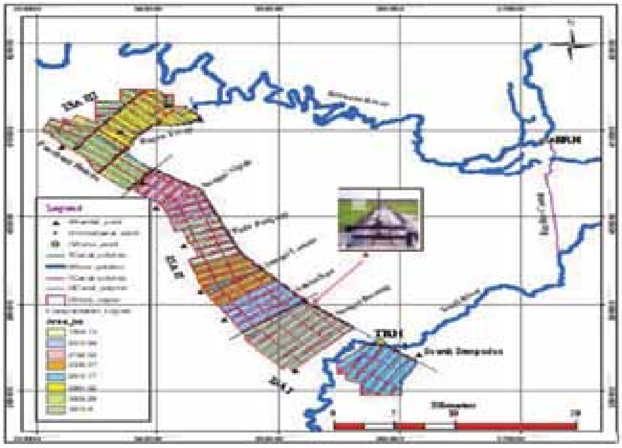
The study area is the Tanjung Karang Rice Irrigation Scheme (TAKRIS), which is located at 3°25′ - 3°45′ N latitude and 100°58′ - 101°15′ E longitude in the state of Selangor, Malaysia (see Fig.1a). The total command area of the scheme is about 18000 ha. Rice is grown two times in a year, mainly from August to January (main/wet season) and February to July (off/dry season). The Bernam River is the only source of water for the irrigation supplies, which is diverted by the Bernam River Headworks (BRH) into the feeder canal. Water is conveyed into the Tengi River and thence to the intake point of the main canal at Tengi River Headworks (TRH). The distance from BRH to TRH is about 36 km. Irrigation water is directly delivered from the main canal to the tertiary canals which are spaced at 400 m apart. A standard irrigation block has a net command area of about 50-300 ha (Fig.1b). Each row of irrigation blocks receives water in their paddy plots directly from two tertiary canals. A pump house was constructed in 1962 on the lower reaches of the Bernam River in Bagan Terap to provide water supply for approximately 1000 ha in the northern portion of the area. Nonetheless, this study did not consider the command areas under the pumping scheme because this command area is irrigated through different canal networks at a relatively higher elevation than the gravity fed paddy areas.

Data Collection and Database Development

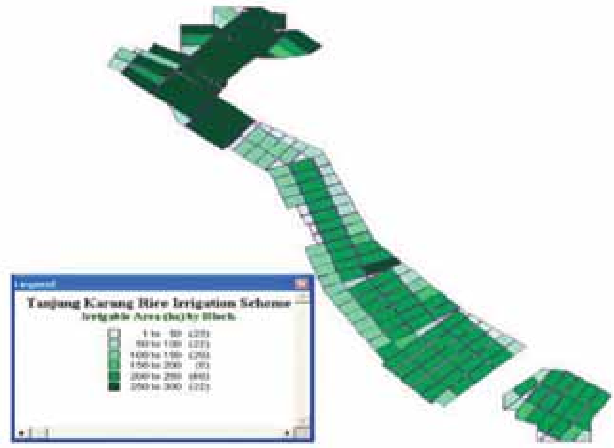
Data and related information were obtained from relevant government agencies such as the Tanjung Karang Rice Irrigation Scheme Authority (IADA) for different ISAs, the Department of Irrigation and Drainage (DID), Department of Agriculture (DOA), Department of Survey and Mapping Malaysia (JUPEM) and Malaysia Meteorological Department (MMD), as shown in Table 1. The detailed features of the irrigation scheme were obtained from the Department of Irrigation and Drainage (DID). Database development was the crucial task. All the data were properly registered and assembled in the GIS system.

Theoretical Considerations

Water demand estimation is the primary consideration for the irrigation scheduling of a scheme. In Malaysia, the recommended pre-designed presaturation is 2.31 l/s/ha (20 mm/day) for one month and supplementary irrigation requirement is 1.16 l/s/ha (10 mm/day) for the rice irrigation systems. The total water requirement for rice production is about 1000–1300 mm,



(a) Irrigation Scheme



(b) Command Areas by Irrigation Block

Fig.1. Irrigation Distribution Network and Blocks of the Tanjung Karang Rice Scheme

Table 1: Required Information and Data Collected for this Study

No.	Data type	Stations/Organization	Period of record
1	Daily Rainfall	12 Stations (Dept of Irrigation and Drainage)	1970 – 2006
2	Daily weather events	MMD (Malaysian Meteorological Dept)	1990 – 2006
3	Topographic Maps	JUPEM (Malaysian Surveying Department)	Latest 1995
4	Land use map	DOA (Dept. of Agriculture, Malaysia)	2004
5	Irrigation and drainage network maps	DID, Tanjung Karang Irrigation Scheme	2004
6	Configuration of canals and structures	DID, Tanjung Karang Irrigation Scheme	2004
7	Yield data	DOA, Tanjung Karang Irrigation Scheme	2007-2008

depending on the characteristics of the schemes (JICA and DID, 1998). In Southeast Asia, the water requirement for pre-saturation is theoretically 150-200 mm for 2 to 4 weeks, and as high as 650–900 mm with longer duration of 24–48 days (De Datta, 1981; Rowshon, 2009).

Water Balance Model for Paddy Field

The field water balance provides management decisions on how the scheme ought to be operated to ensure better distribution of irrigation water. The generalized water balance equation for the paddy field can be expressed as follows:

$$WS_j = WS_{j-1} + IR_j + ER_j - ET_j - SP_j - DR_j - SR_j \quad (1)$$

Where,

WS_j = ponding water depth in the field during j-th day (mm)
WS_{j-1} = ponding water depth in the field during (j-1)-th day (mm)
IR_j = amount of irrigation water supplied during j-th day (mm)
ER_j = effective rainfall received during j-th day (mm)
ET_j = crop evapotranspiration during j-th day (mm)
SP_j = water lost through seepage and deep percolation loss during j-th day (cm)
DR_j = drainage from paddy fields during j-th day (mm)
SR_j = surface runoff from paddy fields during j-th day (mm)
j = irrigation period in (day).

Effective Rainfall (ER)

Effective rainfall is that portion of rainfall over the command area that potentially could contribute to the water requirements of growing rice in the field. The effective rainfall for the irrigated condition can be determined using the drainage model of the International Rice Research Institute (IRRI, 1977), as follows:

$$ER_j \left(1 - \frac{DR_j}{RF_j + IR_j}\right) * RF_j \quad (2)$$

where,

RF_j = rainfall during j-th week (cm)
DR_j = drainage requirement from the paddy field during j-th week (cm)

When the field water depth exceeds the maximum ponding water depth, the drainage required is:

$$DR_j = WS_j - 1 + IR_j + RF_j + ET_j - SP_j - WSmaxj \qquad \text{when, } WS_j > WSmax_j \quad (3)$$

$$DR_j = WS_j - H_d \qquad \text{If } WS_j > H_d \quad (4)$$

where, H_d is the dike height of the paddy field in cm. A concrete box structure with flashboard or drop-board is placed at the drainage outlet of each plot to store more rainfall and maintain the desired ponding water depth as the season advances. Rainfall in excess of the flashboard height leaves the system as surface runoff (SR_j).

$$SR_j = RF_j + WS_j - BH \tag{5}$$

where, BH is flashboard height in mm.

Presaturation Irrigation Requirements

A very large amount of water is consumed to inundate fields for pre-saturation before planting of the crop. The water required during pre-saturation period can be determined as follows:

$$SAT = \frac{IR_S + EP_S + SP + WS}{IE} \tag{6}$$

Where,

SAT = water requirement during presaturation period (mm/day)
IR_S = water requirement to saturate the soil (mm/day)
EP_s = evaporation loss from saturated soil surface (mm/day)
SP = seepage and percolation losses (mm/day)
WS = additional supply to maintain the initial depth of flooding (mm/day)
IE = overall irrigation efficiency

Normal Irrigation Requirements

The required irrigation water during the normal irrigation period shall be allocated on the basis of equation (7).

$$GIR_j = \frac{(ET_0)_j \times K_c + SP_j - ER_j}{IE} \tag{7}$$

where,

GIR_j = gross irrigation water requirement (mm/day)
$(ET_0)_j$ = reference crop evapotranspiration (mm/day)
SP_j = seepage-percolation loss (mm/day)
ER_j = effective rainfall (mm/day)
K_c = crop coefficient
IE = overall irrigation efficiency is considered to be 45% (DID and JICA, 1998).

Irrigation Supplies for Tertiary Canals

A GIS-integrated programme which had been developed (Rowshon *et al*., 2009) earlier was modified to determine the recommended irrigation supply for the tertiary canals as the season advances. In Tanjung Karang Rice Irrigation System, about 120 tertiary canals distribute irrigation water directly from the main canal to the paddy lots. A pair of tertiary canals passes through each row of irrigation blocks (3-5 blocks) and distributes irrigation water through the

50 mm pipe outlet for each 1.2 ha paddy lot. An empirical equation was developed to compute the recommended irrigation supply for the tertiary canals.

$$q_r = f_i \times \frac{a_i}{A} \times Q_{aV} \tag{8}$$

Where,

q_r = recommended irrigation supply for tertiary canals (m^3/s)

f_i = the operation and management factor to cater the staggered irrigation supply by one month for each ISA (for example, f_i values for offtakes under ISA II and ISA III is zero in February for the off season and August for the main season so that irrigation water supplies only to ISA I and f_i is zero for ISA II and ISA III)

a_i = the irrigation service areas under the individual tertiary (ha)

A = total planted areas of the scheme (ha)

Q_{av} = average daily available discharges for irrigation supply (m^3/s)

i = irrigation offtake structure number

The model can accurately recommend the irrigation supply for all the tertiary canals incorporating the actual field water demand and the available water resources as the season advances. At first, the water demand for each tertiary canal is determined. The command area for each canal is read from the GIS feature layer "Tertiary Canal*" while the other inputs are taken based on their location by ISA. After that, the proportional irrigation supplies for the tertiary canals are determined and verified with the total available discharge (*Q_{av}) for irrigation supply during a particular irrigation period (daily, weekly or a specified period). For the proportional allocation, the ratio of the actual planted area under each tertiary canal to the total actual planted area of the scheme is incorporated with the available water. To cover the irrigation supply for the targeted irrigation service areas throughout the scheme, the recommended irrigation supply (q_r) for each pair of irrigation offtakes will be normally less than or equivalent to the allowable irrigation supply (based on the available discharge for the irrigation supply). This condition must be followed to meet the recommended field water demand, unless otherwise irrigation distribution will be uneven. The prior aim must be to strengthen the regulation of the gate opening of the tertiary canals. Otherwise, some areas may not receive the right amount of irrigation supply and result in uneven allocation. As irrigation supply is staggered by one month for each ISA, the irrigation manager may adjust the irrigation supply among tertiary canals based on the priority of water demand pattern by ISA. However, the total recommended supply for all the tertiary canals must be less than Q_{av} for a particular day. The recommended irrigation supply for the tertiary canals can be higher than the allowable irrigation supply when Q_{av} in the main canal is sufficient to do so. However, this condition is rare during the peak water demand period. This situation can be achieved if a significant amount of rainfall is utilized as supplementary irrigation in paddy fields.

Water Productivity Index (WPI)

The water productivity index measures the effectiveness of the irrigation system in terms of gross rice yield and the total volume of water applied. Both the increase of rice yield per hectare and the increase of the water use efficiency are essential to improve Water Productivity Index (WPI). It is expressed as follows:

$$WPI = \frac{Y}{q} kg/m^3 \quad (9)$$

where,

Y = the specific yield, which is the yield per ha (kg/ha) for the season in the area concerned.

q = the specific supply, which is the total supply including rainfall per ha for the season in the area concerned, m^3/ha.

ARCGIS-VBA USER-INTERFACE

A GIS-based user-friendly interactive system TAKRIS-SWPI (Spatial Water Productivity Index for Tanjung Karang Rice Irrigation Scheme) was developed to determine the spatial water productivity index for the rice-based system. The workflow diagram of the TAKRIS-SWPI is shown in Fig.2. TAKRIS-SWPI is an ArcGIS-VBA user-interface within the powerful ArcGIS environment which is structured with irrigation deliveries module and several sub-modules. The programme determines day-to-day irrigation supplies for the Tanjung Karang Rice Irrigation Scheme using the user-interface that allows the calculation of the spatial water productivity index after completing the irrigation season.

GIS User-interface Operation Procedures

On the activation within the ArcGIS Software, the menu “TAKRIS-SWPI” appeared directly on the Menu Bar in the ArcMap Window, as shown in Fig.3. By selecting the menu item, “Open Spatial WPI (SPWI)”, the programme allows viewing of the dialog wizard of the TAKRIS-SWPI, as shown in Fig.4.

Recommended Irrigation Supplies for the Tertiary Canals

The module simulates the recommended irrigation supplies on a daily basis for all the tertiary canals as the season advances. A dialog window (see Fig.5) appears by clicking on the command button “Recommended Irrigation Deliveries” in Fig.4. To run the programme, the daily inputs, such as Present Standing Water Depth (SW), Recommended Standing Water Depth (SW_{max} or ASW), Reference Crop Evapotranspiration (ETo), Seepage and Percolation (SP), expected daily Rainfall (RF), Crop-coefficient (k_c) and Irrigation Efficiency (IE), are required.

The programme allows computing the present standing water depth for each ISA using the water balance equation. This can also be obtained from field monitoring. The standing water depth can be adjusted as per the management decision for providing irrigation supplies to the priority service areas. The FAO Penman-Monteith is used for the daily inputs of ETo. The rainfall (RF) on the previous day is taken under each irrigation service area (ISA). Stochastic

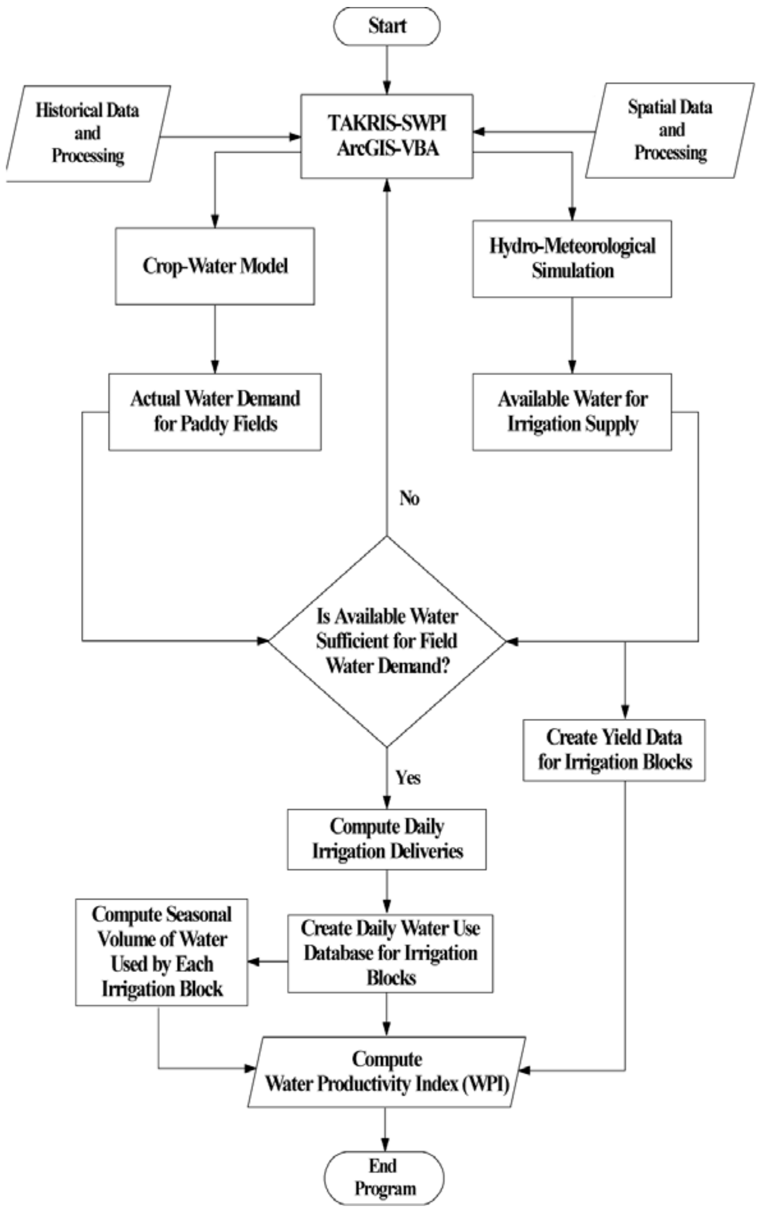


Fig.2: ArcGIS-VBA Algorithm for TAKRIS-SWPI

rainfall generation model can also be adopted in the irrigation scheduling. These values can be fed into TextBoxes by simply clicking on the Command Buttons in the sub-modules of FAO Penman-Monteith method (Allen *et al*., 1998) and the stochastic rainfall model (Fig.5).

By clicking on the command button, “Inflow at TRH” in Fig.5, the available discharge for the irrigation supplies (i.e. 26.54 m^3/s on 10 November, 2008) can be estimated at the intake point of the main canal. A sub-routine for the Autoregressive model is linked with the command button “Inflow at TRH”. This can be fed directly upon getting the observed data at the intake point. The installation of the real time discharges monitoring station is in progress. To ensure

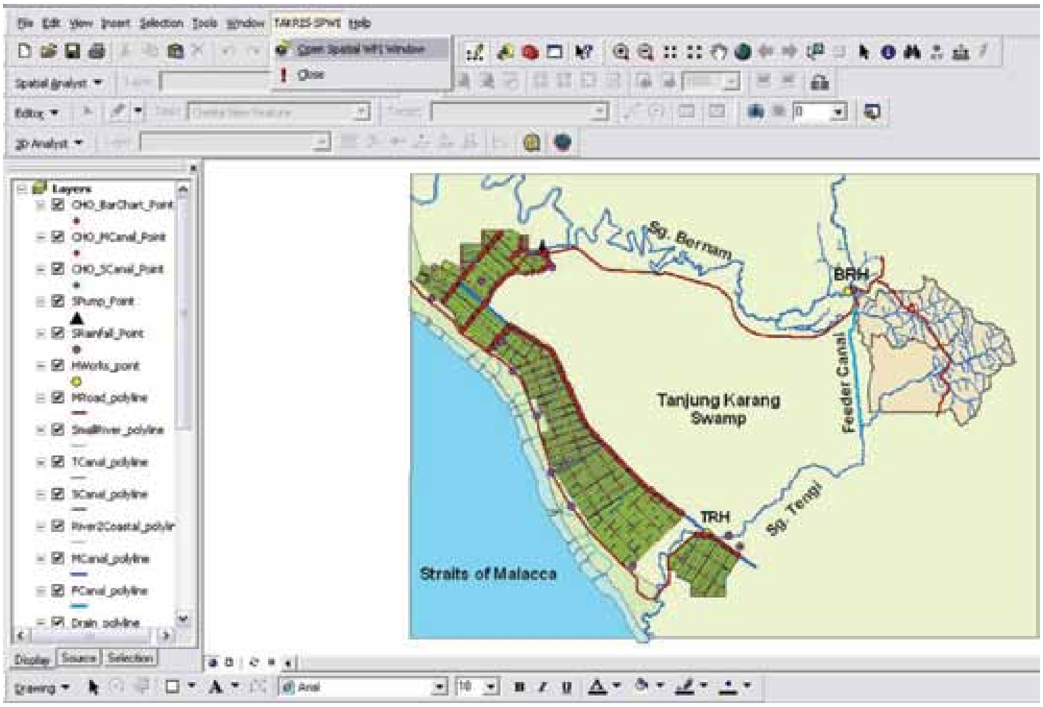


Fig.3: TAKRIS-SWPI Menu showing the Tanjung Karang Irrigation Scheme

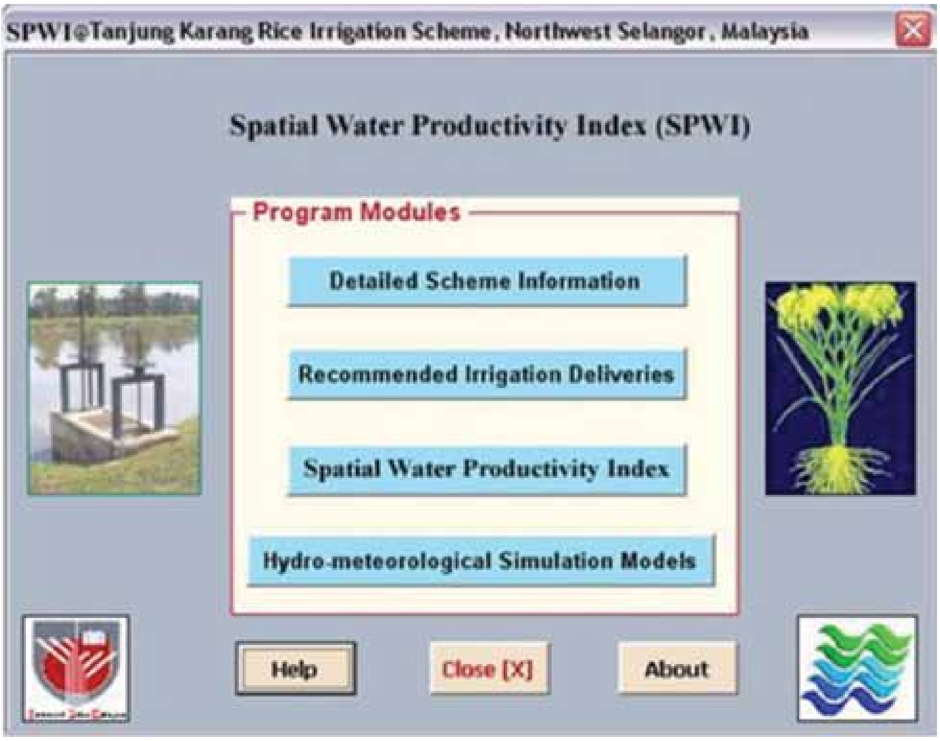


Fig.4: Dialog Wizard for Irrigation Deliveries and WPI

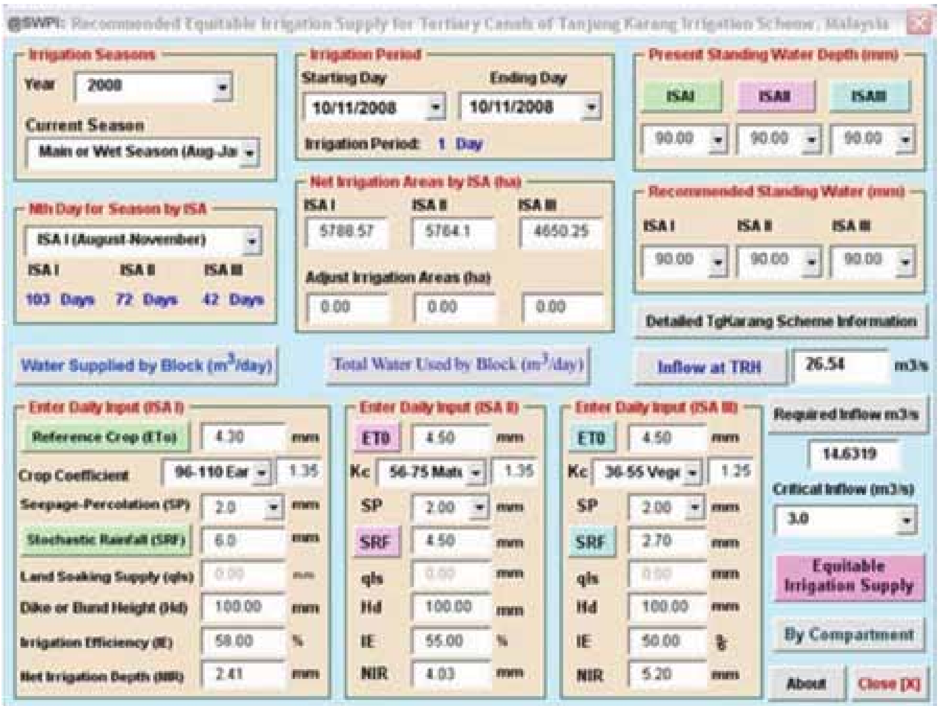


Fig.5: Dialog Wizard for Recommended and Equitable Irrigation Water Allocation by Tertiary Canals, 10 November 2008

the irrigation supply for all the tertiary canals on a particular day, the total recommended irrigation supply should not exceed the total available discharge i.e. 14.63 < 26.54 m^3/s. This condition can ensure an adequate irrigation supply for the targeted service areas. The total required discharge for the recommended supply is computed and displayed in the TextBox (i.e. 14.63 m^3/s) while changing the values of parameters in Dialog Wizard. The programme allows irrigation supply to the areas with priority by optimizing the input parameters. This decision is dependent on several factors including ponding water depth, utilization of rainfall, crop growth period and intermittent agricultural practices. After checking and adjusting the inputs, the daily recommended supplies for the tertiary canals are simulated. After this, the irrigation supply by block is computed by the command button “Water Supply by Block (m^3/day)” and then the total water used (Irrigation and Rainfall) by each irrigation block is computed and stored in the database by the command button “Total Water used by Block (m^3/day)”.

Reference Crop Evapotranspiration (ETo) Calculation

The FAO Penman-Monteith method was used to compute the daily reference crop evapotranspiration (Allen *et al*., 1998). A sub-routine which allows the irrigation managers to compute the daily Reference Crop Evapotranspiration (ETo) was developed based on the available meteorological data for a particular day. The system allows for storing all the inputs and outputs into the MS Access database.

Geospatial Water Productivity Index (PWI)

A step-by-step calculation of the spatial water productivity index is shown in Fig.6. A dialog window as the one shown in Fig.7 appears by clicking on the command button "Spatial Water Productivity Index" in Fig.4. The "General Information of the Scheme" helps to explore scheme information such as irrigation date and irrigation command areas under Block, Compartment, Irrigation Service Area and Irrigation Season. An easy update system of the associated database keeps the system to be always updated in respect of the real field situation.

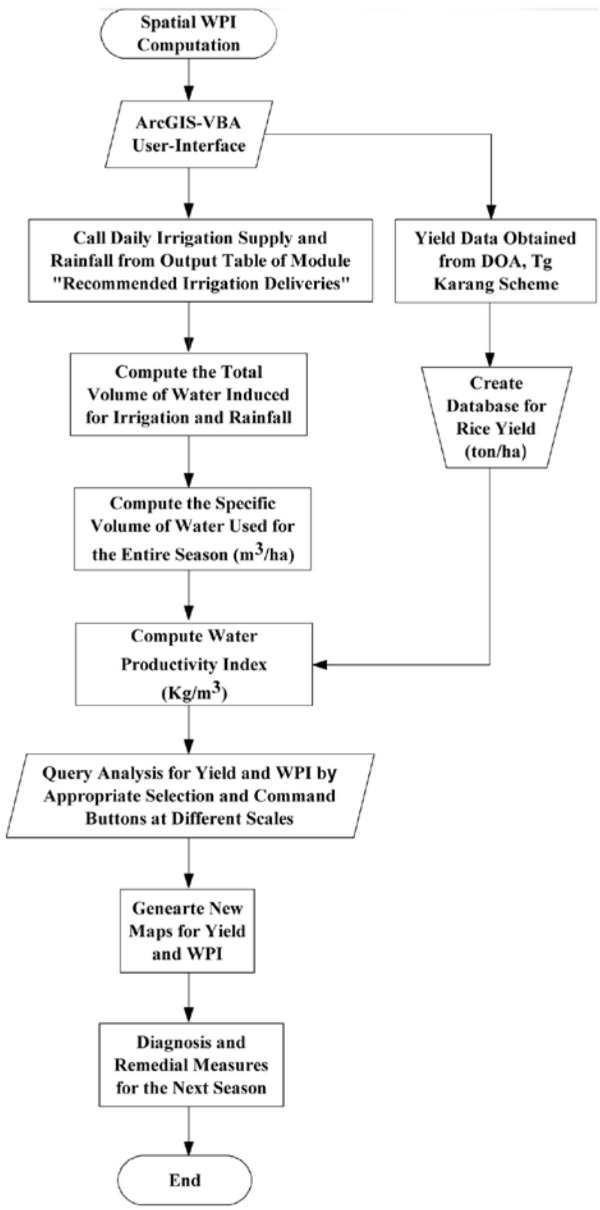


Fig.6: ArcGIS-VBA Algorithm for Spatial Water Productivity Index Calculation

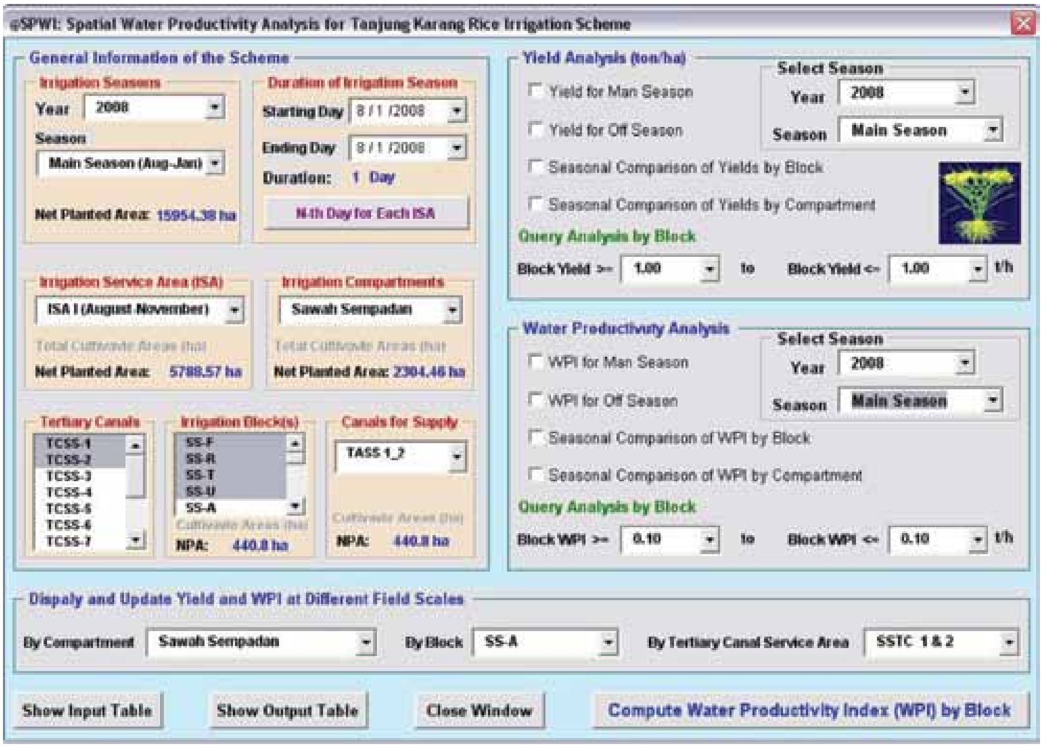


Fig.7: Dialog Wizard for Computing Spatial Water Productivity Index (SPWI)

The water productivity index is one of the important performance indicators which describe the relationship between water use and yield. The programme provides information for the scheme at different scales, i.e. irrigation block (50-300 ha), irrigation service area under each tertiary canal (2-5 irrigation blocks), irrigation compartments (8 compartments) and the scheme. After developing a proper database on the basic inputs by irrigation block, the water productivity index (WPI) and yield can be computed and analyzed at different scales. The command button "Compute Water Productivity Index (PWI) by Block" computes the spatial WPI for irrigation blocks. The user needs to select the appropriate items and options for viewing the results from Fig.10. Many command buttons shown in the parts, "Yield Analysis (tonnes/ha)" and "Water Productivity Analysis", are available to analyze the spatial rice yield and WPI. The other part, "Display and Update Yield and WPI at Different Scales", allows updating of data and provides yield and WPI information for each compartment, block and irrigation blocks (2 - 5), which are usually under two Tertiary Canals. The entire information can be displayed using the command buttons "Show Input Table" and "Show Output Table".

RESULTS AND DISCUSSION

Simulation of the Recommended Daily Irrigation Deliveries

To simulate the recommended supplies for the equitable water allocation, the ratio of the actual planted area under each tertiary canal to the total actual planted area of the scheme is incorporated with the available discharge for irrigation supply and the actual water demand. To cover the irrigation supply for the targeted service areas of the scheme, the recommended equitable irrigation supply through each irrigation off-take structure should be less than or equivalent to the allowable irrigation supply. An allowable irrigation supply for a particular canal is the product of the available discharge for the irrigation supply in the main canal and the ratio of the actual planted area under each tertiary canal to the total actual planted area of the scheme.

Irrigation supply can be adjusted based on the priority of water demands by the tertiary canals within ISAs. For a particular day, the total recommended supply for the scheme must be less than the available discharge for the irrigation supply in the main canal (i.e. 14.63 < 26.54 in Fig.5). Then, the recommended irrigation deliveries for the tertiary canals are shown by clicking on the command button "Equitable Irrigation Supply" at the bottom right corner in Fig.5. The output is displayed instantly as shown in Fig.8. The gate operation for the irrigation off-take structures must be strengthened to release the recommended deliveries for the tertiary canals. The results displayed in maps, tables, and graphs can help the irrigation manager to diagnose the irrigation system and take the proper decisions for the gate operations, such as on 10th November in the main season, the recommended supplies among tertiary canals with respect to the allowable and design supplies are shown in Fig.8.

The name and information can be displayed together on the screen whenever the cursor is placed over the particular object of the map layout. This facilitates the irrigation manager to

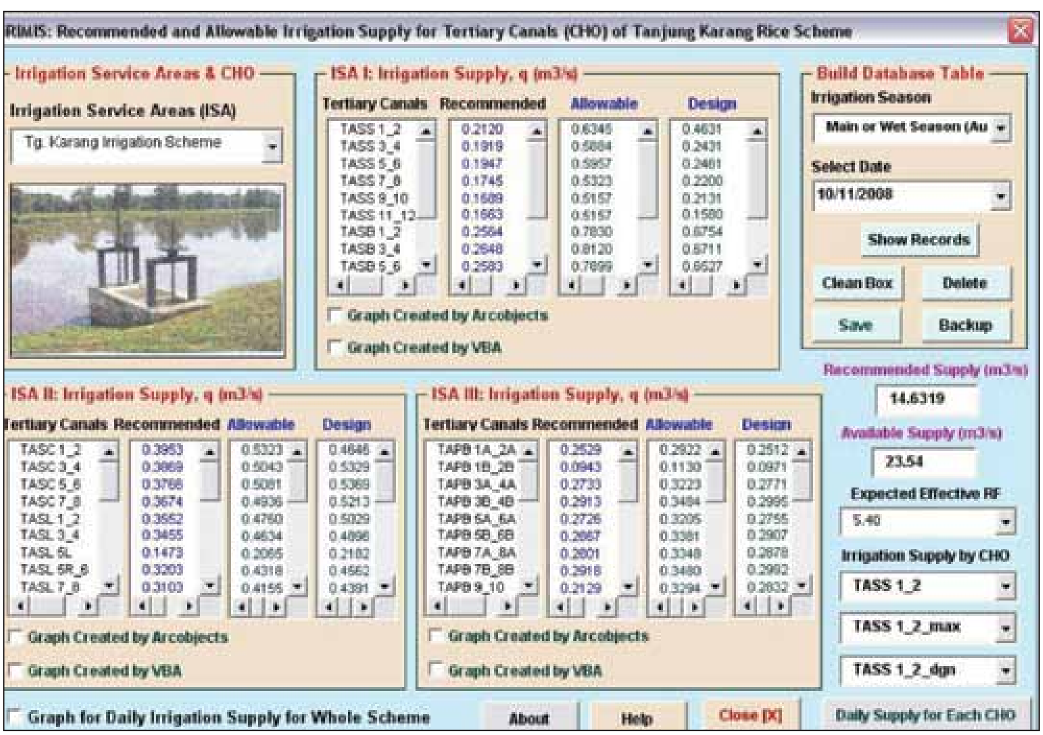


Fig.8: The Output Dialog Wizard for Recommended and Equitable Irrigation Water Allocation for all Tertiary Canals on 10 November 2008.

determine the amount of deliveries for each irrigation block and the irrigated service area. The spatial distribution of the total amount of irrigation supply throughout the irrigation blocks can be computed and displayed (*see* Fig.9) by clicking on the command button “Water Supplied by Block m^3/day” from Fig.5.

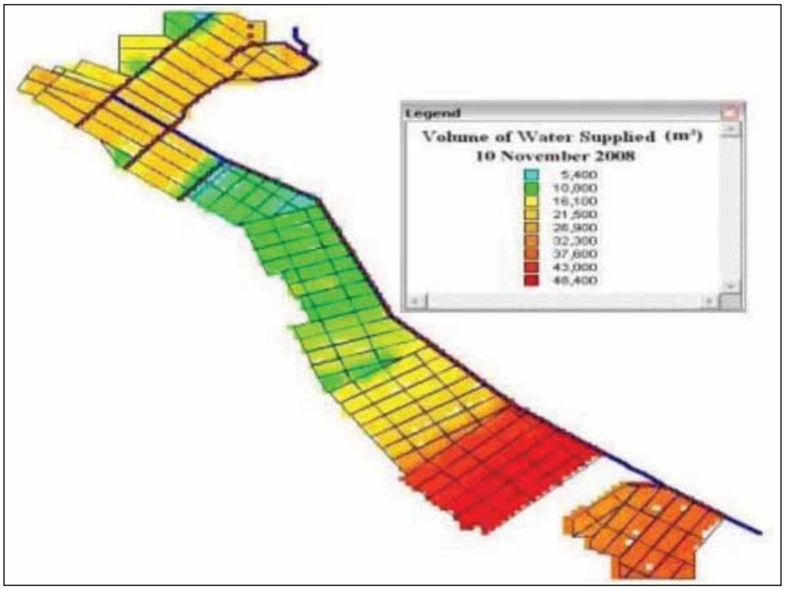


Fig.9: Volumetric Irrigation Distribution in Irrigation Blocks on 10 Nov 2008

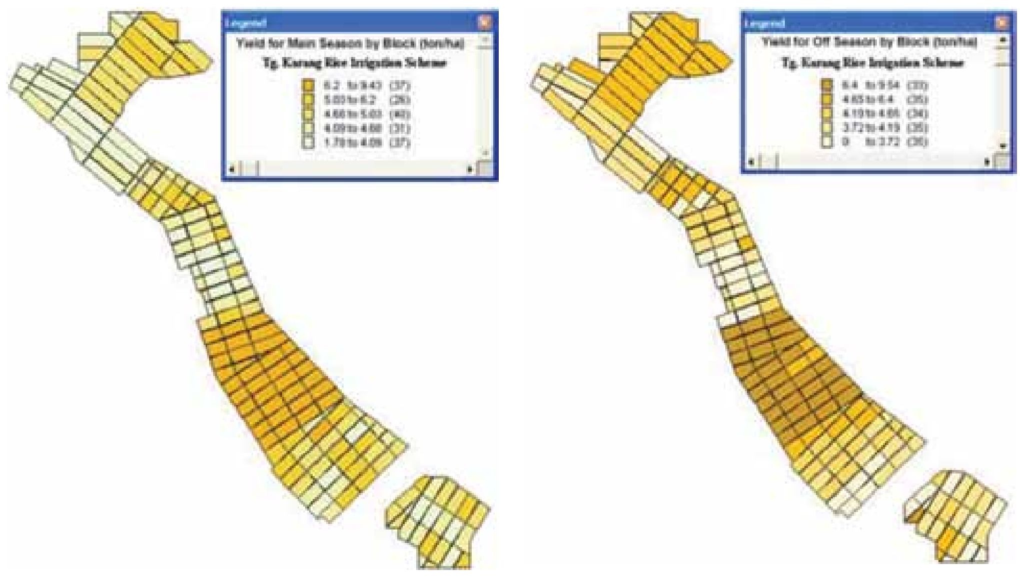
Record keeping on the daily irrigation task in the database is essential to diagnose the irrigation distribution for each tertiary unit as the season progresses. The irrigation off-take gate at the head of the tertiary canal is called CHO (Constant Head Orifice). The programme provides tracking of seasonal irrigation supply on the daily basis for each row of the tertiary canals by clicking on the command button “Daily Supply for Each CHO” after selecting the tertiary canals in the ListBox “Irrigation Supply by CHO”.

Seasonal Yield Analysis by Irrigation Block

The yield of the scheme for 1998-2002 obtained was around 4.47 t/ha in the off season and 4.65 t/ha in the main season, respectively. The thematic map created for the average yield obtained for the main season and the off season of the scheme in 2008 is shown in Fig.10.

Water Productivity Index (WPI)

The analysis for the entire irrigation season was done by summing the daily data to compute the water productivity index. The programming module can call on the database of the spatial and temporal data to produce the tabular and graphical output by SQL (Structure Query Language). The programme allows updates of the database on a random basis. The browser window displays when the user selects an option from the ListBox within the GroupBox window “Display and Update Table”. The user can update information during on-going seasons



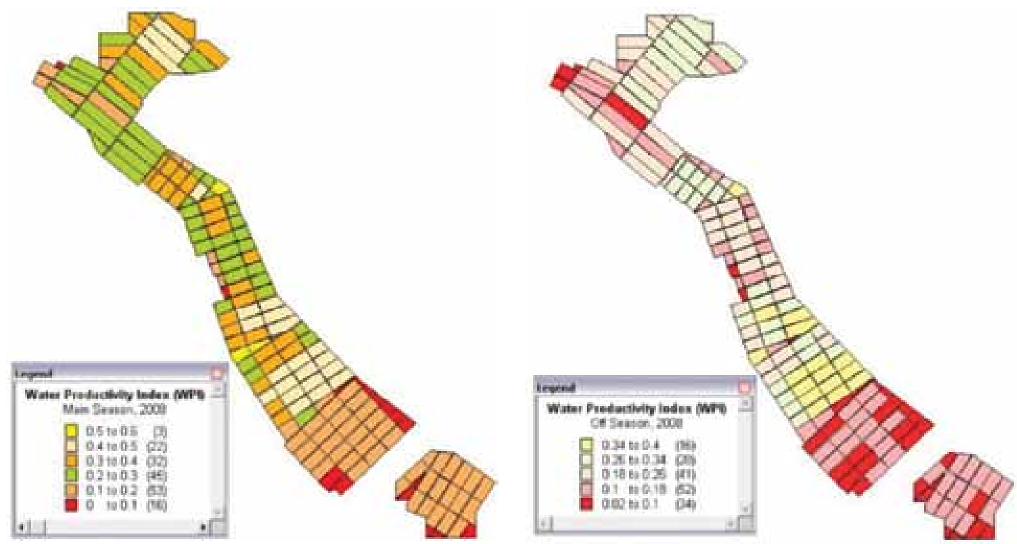
(a) Main Season (b) Off Season

Fig.10: Seasonal average rice yields by block in 2008

through options available in the dialog windows. The yield database file for an individual block is developed by season.

The water productivity index can be computed and stored in the output database using the command button "Compute Water Productivity Index (PWI) by Block" as shown in Fig.7. The computed WPI can be displayed instantly by selecting the check boxes "WPI for Main Season" and "WPI for Off Season" from Fig.7. The spatial distribution of the WPI within irrigation blocks for the main season and off season is shown in Fig.11a.

The Water Productivity Index provides a measure of the irrigation system's effectiveness in terms of gross grain yield. The values of the WPI ranged from 0.02 to 0.57 kg/m^3 in the main season and from 0.02 to 0.40 kg/m^3 in the off-season, respectively (*see* Fig.11b). The average values for the main season and off-season were found to be 0.25 and 0.21 kg/m^3, respectively. This is below the desirable targets of 0.30 to 0.60 kg/m^3. The two factors which directly affect the WPI are specific supply (m^3/ha) and specific yield (kg/ha). The specific supply can be reduced through utilization of rainfall. An acute shortage of the irrigation supply is the main reason for the low productivity in the off-season. The thematic map gives an excellent explanation of the spatial variation of WPI among the irrigation blocks. Meanwhile, query analysis can be done for the yield and WPI by selecting the range on the basis of irrigation block. The WPI > 0.40 for the main season can be retrieved from the database and is displayed on the irrigation blocks map, as shown in Fig.12. The highest productive irrigation blocks are shown in the highlighted area in following figure.



(a) Main Season, 2008 (b) Off Season, 2008

Fig.11: Seasonal Spatial Distribution of WPI for Irrigation Blocks in 2008

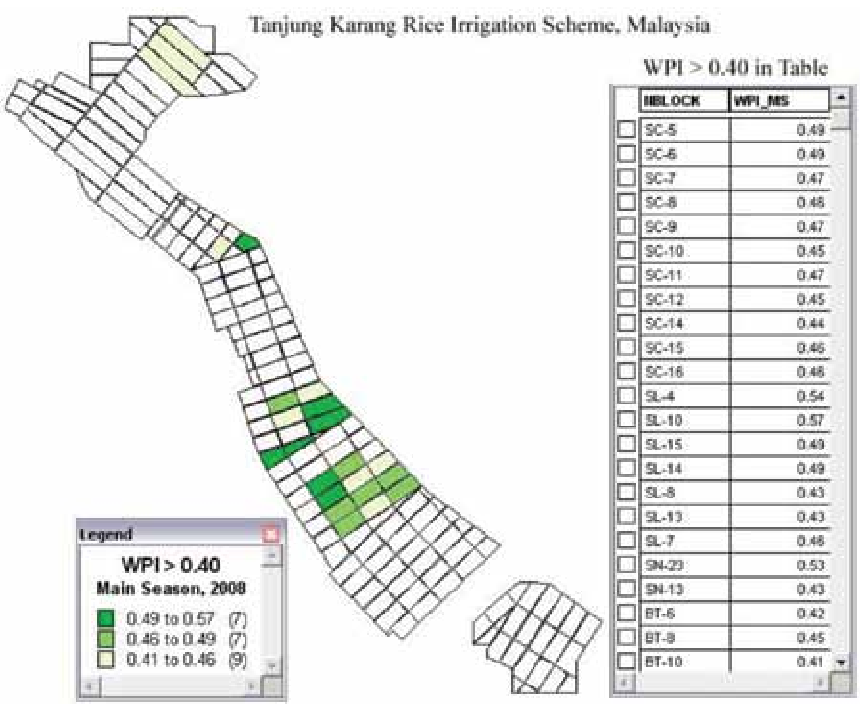


Fig.12: Irrigation Blocks where WPI > 0.40 for Main Season in 2008

CONCLUSIONS

To get an accurate calculation of Water Productivity Index (WPI) is obviously a difficult task as it requires the calculation of the amount of water delivered or agricultural water use for each irrigation operation. It is normally calculated using the monthly or seasonal data obtained from the projects and/or various organizations. This paper focuses on a systematic computation procedure to calculate the volume of water used from the beginning to the cut-off of irrigation supply for rice production. A GIS-based user-interface programme was developed to compute and depict the spatial variation of the WPI within the irrigation blocks. There is a significant spatial variation of WPI among the irrigation blocks in every season. The temporal variability was not discussed in this paper as the programme was run to estimate the quantity of water used in rice production only for one year. This can be done after several years of running the programme. More importantly, the programme is useful to be used in determining the rate of increase or decrease of both rice production and water productivity index. The programme can be extended on the basis of the smallest scale such as each irrigation or paddy lot. There are about 17000 paddy lots of approximately 1.2 ha to 2 ha each. At the moment, it is difficult to get yield data for each paddy lot from the farmers. This programme can be used to take possible remedial measures and rectification on water management model, as well as irrigation operation to increase water productivity in the next season as the analysis of the spatial variability can clearly depict the low productive areas. This approach could be useful to procure the right information about irrigation water use for crop production and to investigate the rate of seasonal changes of water productivity index. Apparently, this useful information is probably important for the planning and decision making on water use for other water-related projects either in agriculture or other sectors. This is because the approach can depict the gaps between the existing and appropriate water management practices using the spatial variability of WPI. Suitable interventions could be made to fill the gaps and to enhance water use efficiency at field level and can also help in saving irrigation water in the forthcoming season. The analysis shows that the potential of the crop-water simulation models in considering varying soil, water, crop and climate conditions can be incorporated to determine WPI accurately. In addition, this systematic approach could be adopted for any irrigation system with the required modification.

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