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Water distribution and water use assessment in rice cropping systems

M. Aminul Haque[1], T.S. Lee[2] and S.M. Bockari-Gevao[3]

Abstract

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This study was carried out to analyze the ways of water distribution in a rice growing area during the pre-saturation and normal irrigation supply periods and to assess water use (WU). The analyses were conducted using field data collected at the Besut rice irrigation scheme located in the state of Terengganu, Malaysia. The scheme comprises two sub-schemes, which are further subdivided into compartments and blocks. Based on field water requirements during the pre-saturation and normal irrigation supply periods and available flows at the intake structures, canal simulation was performed using the CanalMan Model. Results have shown that pre-saturation should not be done continuously unless flow rates are 9.00 m^3/sec and 3.00 m^3/sec for the Besut and Angga Barrages, respectively. If the respective flow rates fall below these values, then pre-saturation should be done in two phases. However, when the flow rate is between 5.00 and 5.50 m^3/sec at Besut Barrage, pre-saturation is recommended to be carried out over three phases. During normal irrigation supply period, flow rates of 5.00 m^3/sec and 1.50 m^3/sec for the Besut and Angga Barrages respectively, are to be maintained for the whole irrigation scheme. In irrigation block-wise, two WU-based performance indices, namely, adequacy (AI) and water productivity (WPI) were computed. The average water productivity was 0.31 kg/m^3 and 0.25 kg/m^3 during the main season and off-season, respectively. Two

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[1]Ph.D.(Water Resources), Scientific Officer, Water Resources Planning Organization, Ministry of Water Resources, House No. 103, Road No. 1, Banani, Dhaka-1213, Bangladesh [2]Ph.D.(Irrigation and Drainage), Assoc. Prof., Faculty of Engineering, Universiti Putra Malaysia, Serdang, 43400 Selangor DE, Malaysia [3]Ph.D. (Farm Machinery), Senior Lecturer, Njala University College, University of Sierra Leone, PMB, Freetown, Sierra Leone
Corresponding e-mail: maminul03@yahoo.com

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WU indices, WPI and AI, ranked the performance of the blocks and identified those having problems in water allocation and utilization. These indices revealed that the blocks using more water performed poorly in terms of water productivity. These indices could be used to rectify uneven distribution of water in the scheme.

Key words : canal flow simulation, water allocation, adequacy and rice irrigation

In many countries around the world, there is an increasing concern about the performance of irrigation schemes because many schemes are not producing the expected returns, or they are suffering water supply restrictions and/or water quality problems. Although good on-farm irrigation is crucial for good performance of any scheme, the bottleneck is often in the irrigation delivery system. An inappropriate system design may be the root of some of the problems, but proper management is also essential for the effective operation and maintenance of irrigation water delivery systems (Malano *et al.*, 1999). Various performance evaluation terms are used to quantify how close the irrigation system is to an ideal one. Traditional analyses of irrigation performance, especially the concept of irrigation efficiency, can mislead planners and policy makers as water availability at the river basin level becomes the primary constraint to agricultural production (Perry, 1999). Based on a review of the literature concerning indicators of irrigation performance, Rao (1993) found that the performance of an irrigation system could be evaluated in two categories, namely, water delivery system and irrigated agriculture system.

Malaysia is a rice growing country and, with the sophistication in rice cultivation practices, emphasis has been placed on farm water management. Water shortages have become more frequent and farmers often face deficiencies in water deliveries, resulting in reduced yields and incomes. Furthermore, poor management of available water for irrigation, both at system and farm level, has led to a range of problems and further aggravated water availability, and has reduced the benefits of irrigation investments. More efficient irrigation must be introduced if more food is to be produced at the same time as water is diverted to other uses. Increased efficiency in the use of water is essential for future food security in Asia where rice production has to be increased by 70% of the present amount by the year 2025 (Hossain, 1997; Tuong and Bhuiyan, 1999). It is clear that irrigation service today has to take on multiple objectives and aim at specific targets with irrigation performance no longer measured by just how well water is delivered and managed but whether the final output justifies the continued service of irrigation. A saving of 5% in irrigation water can meet 15% of water demand for domestic and industrial sector (Teh, 1998). The challenge is therefore to save water from agriculture sector for eventual transfer to the domestic and industrial sectors. Hence, the primary objective of this study is to investigate areas of effective distribution of available water resources in order to achieve higher water productivity.

Study Area

The study area, Besut irrigation scheme, is located in the northeastern corner of Peninsular Malaysia in the state of Terengganu. The scheme consists of 2 sub-schemes, namely Angga Barrage sub-scheme and Besut Barrage sub-scheme. These sub-schemes are further sub-divided into 4 compartments: one compartment in the Angga sub-scheme (Compartment 2) and three compartments in the Besut sub-scheme (Compartments 1, 3, 4). Compartments 1, 3 and 4 (total 4,017 ha) receive irrigation supply by gravity from Besut River system, while compartment 2 (1,147 ha) receives irrigation supply by gravity also from the Angga River system. Moreover, the scheme area is divided into 39 irrigation blocks or water user's group as shown in Figure 1. The main canals convey water downstream and the water is diverted to secondary and tertiary canals through discharge measur-

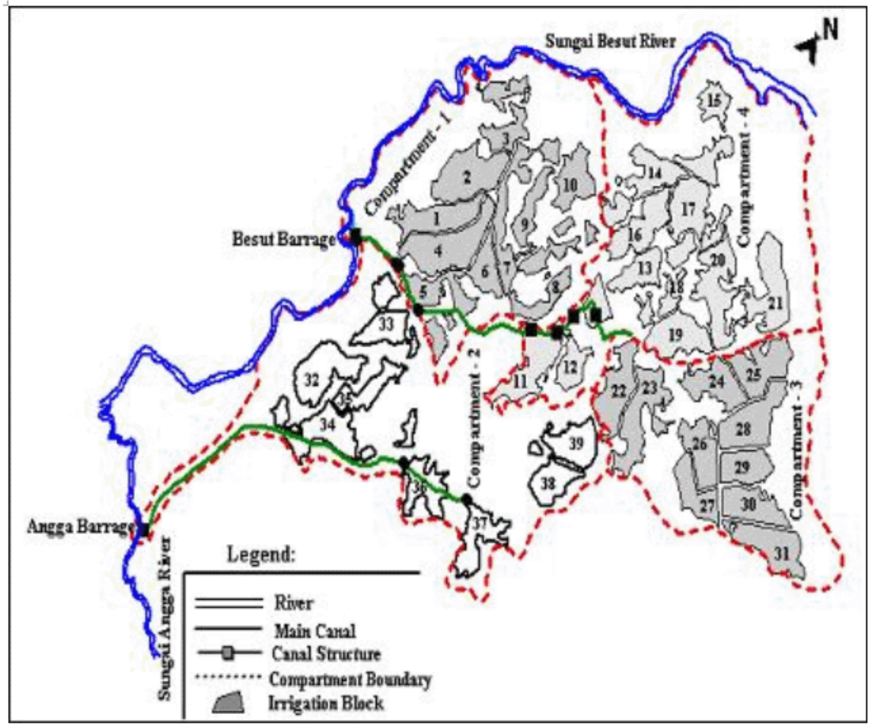

Figure 1. Schematic map of the Besut Irrigation Scheme, Terengganu, Malaysia

ing off-take structures. Irrigation infrastructure of this scheme has been provided for double cropping rice. Water supply adequacy is sensitive to the water levels at the Besut and Angga Barrages. When the water levels of Besut and Angga rivers are above +13.9 m and +16.5 m, respectively, then the whole scheme is irrigated continuously. On the other hand, when the water levels fall below the above desired levels, the scheme is irrigated in a rotational basis. When drought occurs, the drains become supplementary sources of water. At present, water management problems are the most important constraints confronting the scheme in fulfillment of its goal.

The present cropping pattern in the study area is rice-rice regime. The cropping calendar is characterized by two seasons, the main season and off season. The rice variety widely adopted is MR84, which is one of those classified as the short maturation and high yielding type. The rice variety has growth duration of 120 to 125 days. The preferred planting method is that of direct seeding using wet-bed-wet-seeding technique. The field is first pre-saturated (usually referred as the first pre-saturation period) to a standing water level of 100 mm, followed by land preparation and drainage of excess water. Pre-germinated seeds are then sown when there is a thin layer of water in the rice field and the standing water is then allowed to build up in tandem with the height of the rice plant (referred to as the second pre-saturation period). A final water depth of 100 mm is provided to control weed throughout the period of rice plant growth.

Methodology

1. Overview of CanalMan Model

Canal Management Software (CanalMan), developed for performing hydraulic simulations of unsteady flow in branching canal networks, was selected for this study. The CanalMan model was developed by Utah State University, Logan, Utah, USA (Merkley, 1995). This model is based on partial differential equations (the Saint-Venant equations for one-dimensional flow) that allow the flow rate and water level to be computed as functions of space and time. The advantage of the model is that it computes the flow rate and water level simultaneously, so that the model more closely approximates the actual unsteady non-uniform nature of flow propagation in a canal. The model is highly interactive and includes integrated data editing capabilities, with numerous options for canal system configuration. Based on the canal flow simulations, water distribution areas were identified in the study area.

2. Crop Water Demand

In rice irrigation, more than half of the water supplied is used for pre-saturation; i.e. to pre-saturate and inundate fields before planting of crop. During pre-saturation period the system should delivery at maximum capacity in order to reach all the fields as fast as possible so that rice planting could be done without delay. The water requirement for pre-saturation is theoretically 150-200 mm, but can be as high as 650-900 mm when its duration is prolonged, i.e. 24-48 days (De Datta, 1981; Bhuiyan *et al.*, 1995). The water required during land soaking and land preparation period can be calculated as follows:

$$S_k = \frac{\frac{ds}{t_s} + E_v + DP + \mathrm{Re}_k}{8.64E_a} \tag{1}$$

where S_k is the land soaking water requirement [l/s/ha], ds is the depth of water required to saturate the soil [mm], E_v is the evaporation rate [mm/day], t_s is the time required to saturate the soil [days], Re_k is the effective rainfall during time period k [mm/day] and DP is the percolation rate [mm/day].

$$P_k = \frac{\frac{d_p}{t_p} + E_v + DP - \mathrm{Re}_k}{8.64E_a} \tag{2}$$

where P_k is the land preparation requirement [l/s/ha], d_p is the depth of water required for crop submergence [mm], t_p is the time required for land preparation [days], E_a is the irrigation efficiency of the tertiary unit.

The correct amount of irrigation delivery is the key element to improving irrigation management of the scheme. Irrigation supply for a field block through a gate can be estimated according to field water requirements. In normal irrigation supply period, water required can be calculated on the basis of the formula (JICA, 1998) shown below.

$$DWR = \frac{(ET_o * K_c + SP - ERF)}{E_s} \tag{3}$$

where DWR is the diversion water requirement, ET_o is the reference evapotranspiration, K_c is the crop coefficient, ERF is the effective rainfall, SP is the combined seepage and percolation rate, E_s is the overall irrigation efficiency. The value of E_s, the overall irrigation efficiency, includes irrigation efficiency and conveyance efficiency along the secondary canals, and is believed to be 45% (JICA, 1998). For soil saturation depth (ds), the Department of Irrigation and Drainage (DID), Malaysia standard value of 150 mm is applied. For standing water depth (d_p), 100 mm is used for the pre-saturation period. Percolation values were obtained from operation and maintenance manuals collected from DID local office.

Crop evapotranspiration (ET_c) is a key factor to determine proper irrigation schedule and to improve water use efficiency in irrigated agriculture. ET_c can be estimated by a reference crop evapotranspiration (ET_o) and crop coefficient (Doorenbose and Pruitt, 1977; Kang, 1986; Kang *et al.*, 1992; Kerr *et al.*, 1993). ETo can be estimated by many methods (Jensen, 1974; Hill *et al.*, 1985; Kang *et al.*, 1994). These methods range from the complex energy balance equations (Allen *et al.*, 1989) to simpler equations that require limited meteorological data (Hargreaves and Samani, 1985). According to Smith *et al.* (1992), the Penman-Monteith method gives more consistently accurate ET_o estimates than other ET_o methods. Md Hazrat *et al.* (2000) also recommended this method after applying it the Muda Irrigation Scheme in northwest Malaysia. Therefore, reference evapotranspiration was estimated by using Penman-Monteith equation as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.3u_2)} \quad (4)$$

where ET_o is the reference crop evapotranspiration [mm/day], R_n is the net radiation at the crop surface [MJ/m^2/day], G is the soil heat flux density [MJ/m^2/day], T is the air temperature at 2 m height [º C], u_2 is the wind speed at 2 m height [m/sec], e_s is the mean saturation vapour pressure of the air [KPa], e_a is the mean actual vapour pressure of the air [KPa], (e_s - e_a) is the saturation vapour pressure deficit [KPa], Δ is the slope vapour pressure curve [k Pa /º C], γ is the psychometric constant [k Pa / º C] and 900 is a conversion factor. The data of temperature, relative humidity, wind speed and sunshine hours were used for estimating reference evapotranspiration. The crop water requirement was then determined from the product of reference evapotranspiration and crop coefficient. The crop coefficient K_c values were used (Chan and Cheong, 2001) and shown in Figure 2. The weather data such as temperature, relative humidity, wind speed and sunshine hours of the study area were also collected for a period of 16 years (1985-2000). The recent 40 years daily rainfall data (from 3 rainfall stations in the scheme) used in this study were obtained from the Data Information Section, Department of Irrigation and Drainage (DID), Malaysia.

3. Irrigation Performance Indices

The present irrigation system was evaluated using two performance indices under different categories. The first index (adequacy) describes the water delivery system while the last index, agricultural productivity, describes the irrigated agriculture system.

The adequacy indicator answers the question - to what extent is the quantity of water provided sufficient for growth needs of the crops (Abernethy, 1989). The relative water supply (RWS), defined by Levin (1982), describes the adequacy of water supply. RWS is computed by the following expression:

$$RWS = \frac{IR + RN}{IRG} \quad (5)$$

where IR is the irrigation water supply, RN the rainfall and IRG the gross irrigation requirement. The gross irrigation requirement is computed as the net irrigation requirement (IRN) multiplied by irrigation efficiency, to account for losses during conveyance, distribution and application. Net irrigation requirement (IRN) is computed as in the following expression:

$$IRN = ET_o * K_c + SP - ERF \quad (6)$$

The information about the amount of irrigation water supply (main season) was collected from 39 irrigation blocks during a field survey.

Agricultural production performance indicators include cropping intensity, ratio of area planted and area harvested, annual yield, productivity of land and productivity of water (Rao, 1993). In this study, an attempt has been made to estimate the productivity of water using observed crop yield data (main season). Productivity of water can be expressed as:

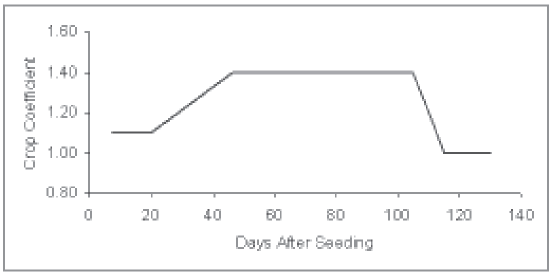

Figure 2. Suggested crop coefficient (K_c) values for rice (MR84 variety)

$$WPI = \frac{CY}{WS} \tag{7}$$

where CY is the crop yield and WS is the water supplied.

4. Canal Flow Simulation

Data used for canal simulation were canal bed width, side slope, canal length, gate structure and specification, water depth, canal cross-section, Manning's roughness and seepage rate. CanalMan input parameters include those data that need to be supplied to the CanalMan database files in order to run the model. These data were obtained from the Map Unit, DID Headquarters, Malaysia. Therefore, canal simulation was performed for the pre-saturation and normal irrigation supply periods. Different flow rates for the Besut and Angga Barrages were used in the canal simulation process because flow rates change during the main season and off-season. The full supply discharges are 9.00 m^3/sec and 3.00 m^3/sec for the Besut and Angga Barrage, respectively. Thus, canal simulation was started under full supply capacity and then with a step-by-step decreased flow capacity approach for the Besut and Angga Barrages. In each simulation process, simulated flow values were compared with design canal flow values (main and secondary canals) to obtain water distribution area. But tertiary canal gates were adjusted with estimated field water requirements. Moreover, canal gate openings were adjusted whenever the simulation flow rate was higher than the demand. Finally, all simulation results were analyzed and possible water distribution area was identified for the pre-saturation period in phases and also repeated for the irrigation supply period for the whole scheme.

Results and Discussion

Results of water allocation and estimation of WU-based performance indicators, as discussed below, highlight the discrepancies in water distribution.

Water Requirements

Water requirement for pre-saturation was calculated taking into account saturation and water layer establishment requirements, open water evaporation and percolation which was estimated to be 250 mm in both the main season and off-season. It was assumed that water layer replacement requirements were allowed each of 150 mm for a pre-saturation period. The mean monthly general weather conditions and water requirements for each month of the year are shown in Figure 3. The evapotranspiration was found to be 4.20 mm/day and 3.99 mm/day for off-season crop and main

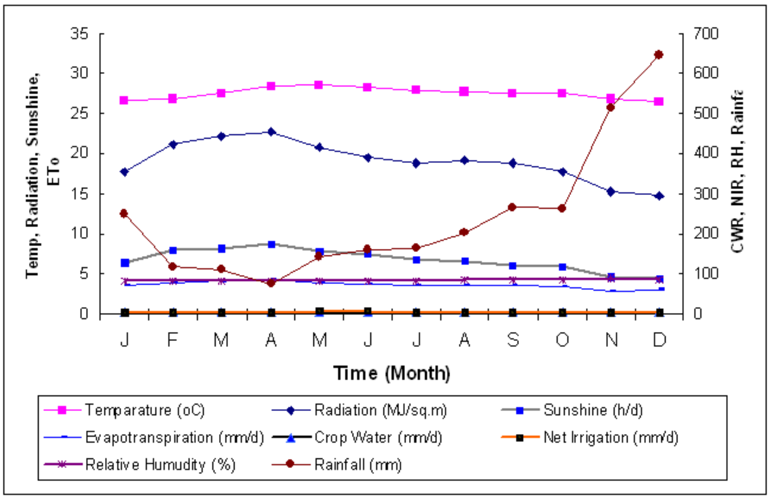

Figure 3. General mean monthly weather condition and crop water for the study area

season crop, respectively. Crop water requirements were higher during off-season crop compared to the main season crop, mainly as a result of prevailing weather condition. The average seasonal rice water consumption was 795 mm, out of which 572 mm (72%) accounted for ET and 223 mm (28%) for percolation. On the other hand, the average seasonal water supply was 1,045 mm of which 732 mm (70%) was supplied by irrigation and 313 mm (30%) by rainfall. It may be pointed out that water requirement was especially high for pre-saturation compared to supplementary supply in the main and off-season.

Water Allocation and Distribution

Based on field water requirements during the pre-saturation and normal irrigation supply periods and available flows at the intake gates,

Table 1. Example showing canal simulation results in the pre-saturation period during the main season and off-season.

Secondary Canal Name	Design Discharge (l/sec)	Simulated Discharge (l/sec)	Canal Name	Design Discharge (l/sec)	Simulated Discharge (l/sec)
			Besut Sub-scheme (Compartments 1, 3, 4)		
Comp - 1		**Intake Gate Flow Rate = 9.00 m³/sec**			
Lubuk Kawah	1075	1080	Lubuk Agu	456	457
FC1/CD	80	80	FC2/CD	80	81
FC1/DE	41	40	FC2/DE	55	56
FC3/DE	80	80	Gong Lawan	46	48
FC4/DE	60	62	Telaga Nibong	1464	1467
Tok Nga	94	94	Kayu Kelat	133	134
Gong Kulim	205	206	Kubang Depu	256	256
Pulau Ribu	254	255	Tok Bugis	124	125
Chenerong	96	97	Gong Rengas	126	126
Comp - 3					
NN1	275	277	NOa	177	178
FC1/NO	155	155	OO1	567	570
PP1	572	571	QQ1	415	416
QQ2	944	945	Q2a	262	260
Q2b	286	285	Q2c	396	396
Comp - 4					
Apal	118	119	FC1/FG	262	262
M1a	264	266	M1b	213	215
HH1	168	170	II1	525	528
IJ	719	719	JK	455	456
KK1	107	110	KL	152	150
LL1	64	66			
			Angga Sub-scheme (Compartment 2)		
Comp - 2		**Intake Gate Flow Rate = 3.00 m³/sec**			
Padang Baloh	756	760	Melintang	86	86
Awek	555	555	RR1	80	81
FC1/RS	32	33	FC2/RS	56	55
SS1	227	230	ST	750	752

water allocation is performed through canal flow simulation. In the period considered for simulation, in the first two weeks, the requirement for rice cultivation comprises only the water requirement for land preparation. During this period, various flow rates for the Besut and Angga Barrages were used in the canal simulation process. Simulation results when compared with the canal design capacity were satisfactory. The simulation results are not compared with actual canal capacity because no such information is available. Table 1 shows a canal simulation for the case of 9.00 m^3/sec and 3.00 m^3/sec for the Besut and Angga Barrages, respectively. The details pertaining to each canal, through simulation, are not reported in this table due to limitation of space. This serves as a check on the design values that were computed much earlier by designers of the scheme.

During the pre-saturation period, it was found that the total scheme area could not be inundated continuously in a single operation unless flow rates are 9.00 m^3/sec and 3.00 m^3/sec for Besut and Angga Barrages, respectively. It was also noted that if flow rate falls below these values then pre-saturation should be done in two phases. Accordingly, the areas recommended for receiving water are identified and are presented in Table 2. Phase I area is supplied first for pre-saturation time of 14 days at 2.10 l/s/ha. After 14 days, the same rate is supplied in Phase II area. But if flow rate is between 5.00 and 5.50 m^3/sec in Besut Barrage then pre-saturation should be done over

Table 2. Water distribution area during pre-saturation period derived from water demand and water availability

Sub-scheme Name (compartments)	Intake Gate Flow (m^3/sec)	Irrigable Area (KPA* Unit)		
		Phase-I Area	Phase-II Area	Phase-III Area
Besut Barrage (1,3,4)	> = 9.00	C-1 (KPA - All); C-3 (KPA - All); C-4 (KPA - All);	---	---
	8.20-8.95	C-1 (KPA - All); C-3 (KPA - 22-5); C-4 (KPA - All);	C-3 (KPA - 26-31);	---
	7.20-8.15	C-1 (KPA - All); C-4 (KPA - 11-20); C-3 (KPA - 22-25);	C-4 (KPA - 21); C-3 (KPA - 26-31);	---
	6.20-7.15	C-1 (KPA - All); C-4 (KPA - All);	C-3 (KPA - All);	---
	5.70-6.15	C-4 (KPA - All); C-3 (KPA - 22-25);	C-1 (KPA - All); C-3 (KPA - 26-31);	--- C-4 (KPA - 21);
	5.00-5.65	C-4 (KPA - 11- 20); C-3 (KPA - 22-23);	C-1 (KPA - All);	C-3 (KPA - 24-31);
	< 5.00	Start pumping for irrigation		
Angga Barrage (2)	> = 3.00	C-2 (KPA - All);	---	---
	2.20-2.95	C-2 (KPA - 32-35);	C-2 (KPA - 36-39);	---
	1.50-2.15	C-2 (KPA - 32, 33, 35);	C-2 (KPA - 36-39);	---
	< 1.50	Start pumping for irrigation		

***KPA- Kumpulan Pengguna Air [local Name; i.e. irrigation water user's group]**

All denotes all KPA units, C denotes compartment, KPA - 22-25 denotes from unit KPA 22 to unit KPA 25 etc.

three phases. In this case, each phase is supplied for pre-saturation time of 21 days at 1.38 l/s/ha. However, when the flow rates fall below 5.00 m^3/sec and 1.50 m^3/sec for Besut and Angga Barrage respectively, then pre-saturation inundation should be carried out using recycling pumps. In this case, the drains would be utilized as supplementary sources of water, which is pumped up to irrigation canals by six recycling pumps.

After pre-saturation, from the fifth week onwards, the irrigation water supply period commences for the next 100 days. During this normal irrigation supply period, 5.00 m^3/sec and 1.50 m^3/sec flow rate for Besut and Angga Barrage, respectively must be maintained throughout the entire period. If available flows fall below the expected values stated above, then the simulation process can be repeated to identify optimal area for irrigation and also areas that may be best left alone in view of inadequate flows available.

Irrigation Performance

The adequacy of water supply to various blocks was characterized by estimating relative water supply (RWS) for each block for the main season of 2000-2001. The block-wise RWS values for the main season are shown in Figure 4. Values of RWS ranged from 0.80 to 3.30. Out of 39 blocks, 29 had RWS value more than 1.5. This indicated that farmers in the canal command areas generally tend to over-irrigate. The irrigation blocks have been classified into five categories, i.e. excessive water surplus (RWS > 3.0), high water surplus (2.0 < RWS < 3.0), moderate water surplus (1.5 < RWS < 2.0), adequate water (1.0 < RWS < 1.5), and water deficit (0.8 < RWS < 1.0). There are two blocks in which the water surplus is more than three times the requirement and fifteen blocks have received more than twice the water required by crop. Three blocks, which are located towards the tail end of irrigation scheme, received water between 0.80 and 1.0 of crop requirement. Blocks receiving high amount of water located mostly towards the head of the main and secondary canals.

The water productivity or the efficiency of water to produce crop growth has been computed from equation (7). The productivity of water ranged from 0.15 to 0.48 kg/m^3. In Figure 5, the irrigation blocks of various compartments have been classified into four groups (< 0.20, 0.20-0.30, 0.30-0.40 and > 0.40 kg/m^3) based on water use efficiency. Out of 39 irrigation blocks, five had a low WPI value (< 0.20 kg/m^3) and eight had high WPI value (> 0.40 kg/m^3). The average water productivity is 0.30 kg/m^3 in the main season. A comparison between the spatial distribution of irrigation blocks in Figures 4 and 5 showed the blocks which were provided with excessive or very high volume of water have used the water, in producing biomass, less efficiently than the areas which received less water. This showed that over-irrigation does not increase productivity proportionately.

Conclusions

Depending on water availability, pre-saturation can be done in one continuous stretch for all the compartments or over different phases as suggested by the simulation. During the irrigation period, if water resources in the river system be deemed inadequate, then the hydraulic simulation can be pursued, to identify the units and compartments that are best irrigate given that not all units can be supplied in view of the circumstances. The canal simulation results therefore can have major implications in relation to future management programs directed toward more decision-making and water-efficient rice culture. The CanalMan model simulates irrigation canals as a means of improving water allocation in rice double cropping systems through proper gate settings and establishing the extent of choice irrigated areas is therefore recommended. The irrigation performance of various blocks was assessed by estimating RWS during the main season and off-season. The RWS values in the main season were found to be from 0.60 to 3.3. Based on RWS values, it was observed that blocks located towards the head of the main and secondary canals mostly received higher amounts of water. The performance evaluation has shown the discrepancies and relative

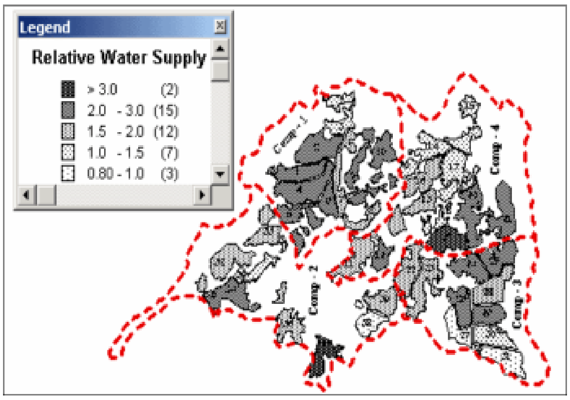

Figure 4. **Block-wise relative water supply of Besut Irrigation Scheme for main season of 2000-2001**

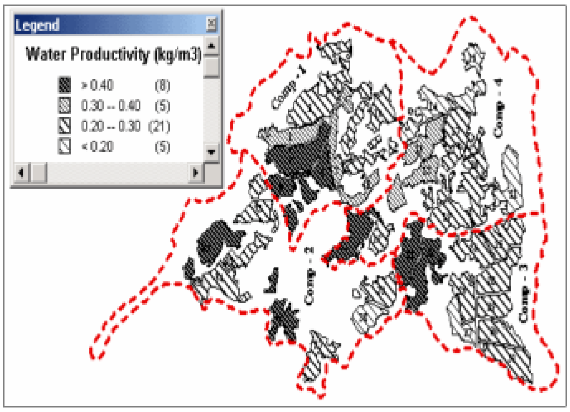

Figure 5. **Block-wise water productivity of Besut Irrigation Scheme for main season of 2000-2001**

ranking of the blocks *vis-a-vis* crop water requirements. Thus regular computed water use assessment could provide the irrigation authority with the means of efficiently managing the irrigation scheme.

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