Analysis of Runoff and Consumptive Use (Evapotranspiration) in Paddy Field Using Water Balance

— Before tertiary canal construction in the Muda Area, Malaysia —

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(Manuscript Received March 10, 1983)

I. INTRODUCTION

Malaysia introduced double cropping of paddy in the Muda area in 1970. This area is a representative rice cultivation district in Malaysia, and the Muda Agricultural Development Authority (MADA) projected double-cropping schemes for Muda a 9600-ha area.

Our team, belonging to the Tropical Agricultural Research Center, has been following up the project in cooperation with MADA. The area observed for the present paper is 730 ha in the Muda area.

Nowadays the most serious problem for agriculture in the Muda area is insufficient irrigation water, especially in the off season, or dry season. Before double-cropping rice was cultivated only in the main (rainy) season.

To solve this problem tertiary canals which will bring efficient distribution of the limited irrigation water to fields were constructed and expected to operate effectively from the next off season. But there is danger of overuse of water afterwards. In this area it is impossible to find new water resources. So it is necessary to establish a reasonable system of water use management, using such techniques as

(i) Staggering
(ii) Border (batas) maintenance and preservation of suitable water depth
(iii) Reasonable water management in fields
(iv) Recycling of irrigation water

The purpose of this analysis is preparation for the evaluation of tertiary canals. In this report we analyzed runoff and consumptive use in the paddy fields of irrigation block ACRBD 4 (Figure 1 and 2) using the concept of water balance. The water depth observation plots are shown as black marks in Figure 2. The observation data used were water supply (rainfall and irrigation water), water depth and evapotranspiration during the main season and the off season in 1980.

* Irrigation Engineering and Rural Planning No. 4, 1983
Basic equation is shown as

$$R + I - O - E.T. = dH \quad (1)$$

$R$ (mm/day); rainfall, $I$ (mm/day); irrigation water, $O$ (mm/day); runoff, $E.T.$ (mm/day); evapotranspiration, $dH$ (mm/day); water depth fluctuation

Although runoff term in eq. (1) was not observed, it was calculated from the water balance equation. Usually runoff coefficient and consumptive-use ($E.T.$) efficiency are defined as the following ratios:

Runoff coefficient $= O / (R + I)$

Consumptive-use ($E.T.$) efficiency $= E.T. / (R + I)$

Rainfall, irrigation water, $E.T.$ and water depth were observed and recorded using automatic rain gauge, gate, $E.T.$ pan and water level meter. In order to look for correlations among the terms multiple correlation analyses were used.

II. WATER BALANCE IN THE OBSERVATION AREA

Monthly water balances are shown in Table 1-1 and 1-2 for the off season and the main season.

1. Water supply

(1) Seasonal and monthly water supply In this report water supply means the total amounts of rainfall and irrigation. There were inflows from one irrigation canals to an other,
Figure 2  The measuring points of the water depth inside ACRBD 4

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but it was difficult to observe the amount (Figure 3), so the inflows were not included in the water supply.

The total amount of water supply in the off season was 1594 mm. The water supply for presaturation was 462.5 mm (29% of the total). In the monthly water supply the highest amount was 455.0 mm in April, and the next was 383.5 mm in May. These months corresponded to the period from presaturation to transplanting.

The total amount of water supply in the main season was 1394.5 mm, less than that in the off season (87.5% of the off season). The larger amount of water supply in the off season is mainly

| Table 1-1  Monthly water balance (off season) |
|----------------|----------------|
| Year          | 1980 (21st Mar. to 9th Sept.) |
| Month         | Presaturation  |
|               |      |      |      |      |      |      |       |       | (R+I) % |
| \( R \) mm    | 7.5  | 118.0 | 240.5 | 116.5 | 165.0 | 280.5 | 28.0  | 956.0 | 60.0   |
| \( I \) mm    | 0    | 337.0 | 143.0 | 116.0 | 42    | 0     | 0     | 638.0 | 40.0   |
| \( R+I \) mm  | 7.5  | 455.0 | 383.5 | 232.5 | 207.0 | 280.5 | 28.0  | 1594.0 | 100.0  |
| \( O \) mm    | 189.0| 305.0 | 216.1 | 130.5 | 64.4  | 212.3 | 10.0  | 1127.3 | 70.7   |
| \( E.T. \) mm | 70.4 | 147.0 | 170.5 | 126.0 | 148.8 | 96.1  | 42.3  | 801.1  | 50.3   |
| \( dH \) mm   | -251.9| 3.0   | -3.1  | -24.0 | -6.2  | -27.9 | -24.3 | -334.4 | -21.0  |
| Average \( H \) cm | -41.7 | 4.4   | 11.2  | 11.2  | 10.7  | 11.9  | 8.4   | 2.3    |

| Table 1-2  Monthly water balance (main season) |
|----------------|----------------|
| Year          | 1980 to 1981 (21st Sept. to 27th Feb.) |
|               |      |      |      |      |      |      |       | (R+I) % |
| \( R \) mm    | 167.0 | 223.0 | 182.0 | 187.0 | 1.0  | 54.5  | 814.5 | 58.4   |
| \( I \) mm    | 0    | 0    | 143.0 | 129.0 | 255.0 | 53.0  | 580.0 | 58.4   |
| \( R+I \) mm  | 167.0 | 223.0 | 325.0 | 316.0 | 256.0 | 107.5 | 1394.5 | 100.0  |
| \( O \) mm    | 2.0  | 148.6 | 166.0 | 257.1 | 104.1 | 175.0 | 852.8 | 61.1   |
| \( E.T. \) mm | 40.0 | 127.1 | 132.0 | 148.8 | 192.2 | 178.2 | 818.3 | 58.7   |
| \( dH \) mm   | 125.0| -52.7 | 27.0  | -89.9 | -40.3 | -245.7 | -276.6 | -19.8  |
| Average \( H \) cm | 15.5 | 15.6 | 13.2  | 12.7  | 8.9  | -17.9 | 8.0    |

caused by the water supply for presaturation. The largest amount of monthly water supply in the main season was November, and the next was December, during the period from transplanting to tilling.
(2) Details of water supply  In the off season 60% (956 mm) of the total water supply was provided by rainfall, and 40% (638 mm) by irrigation. In the main season 58.4% (814.5 mm) of the total water supply was provided by rainfall, and 41.6% (580 mm) by irrigation.

2. Behavior of supplied water

(1) Consumptive use (E.T.)  The average daily amount of E.T. in the off season was 4.8 mm/day, with the range from 3.1 mm/day to 6.4 mm/day. In the main season the value was 5.0 mm/day with the range from 4.0 mm/day to 6.6 mm/day. So there was not much difference in the daily amount of E.T. between the two seasons. The E.T. for both seasons has a tendency to be higher in January, February and March because of dry weather conditions. The ratios of E.T. to the total water supply were 50.3% in the off season and 58.7% in the main season.

(2) Runoff  The total runoff in the off season amounted to 1127.3 mm and was equivalent to 70.7% of the total water supply for the off season. In the main season it was 852.8 mm, 61.1% of the total water supply of main season.

(3) Water detention in the paddy fields (water depth)  There was almost no water detention during the presaturation period, but afterwards the water detention was kept at 10.7 cm depth in the fields on the average in the off season. This value was higher than that (8.0 cm) in the main season, perhaps because the borders (batas) were repaired to ensure enough irrigation water in the off season.

III. INVESTIGATION OF RUNOFF AND CONSUMPTIVE USE (E.T.) USING MULTIPLE REGRESSION ANALYSES

In the present paper water supply includes both rainfall and irrigation. In the analyses it was difficult to separate water supply into independent factors. The reason is that as the free flooding irrigation method was used, irrigation quantity changed in response to rainfall, but
the response was not exact. In spite of this limitation, irrigation and rainfall quantities were measured actually in the field, and the observation method was reliable. So water supply should not be separated into rainfall and irrigation.

Correlations between water balance variances should be examined using multiple regression analyses. As a result the coefficient matrices shown in Table 2-1 and 2-2 were made up.

From these results the following can be said:

The relationship between \((R+I)\) and \(O\) (correlation coefficients 0.7291 in the off season, 0.8430 in the main season) is associated with \(dH\) and \(E.T.\). It can be found from Table 2-1 and 2-2 that when water supply increases, runoff and water depth in a field are increased. The values of these correlation coefficients are larger in the main season than in the off season, because for water-shortage in the offseason it is necessary to keep water deep, which is accomplished by better borders (batas) maintenance in the off season.

IV. INVESTIGATION OF RUNOFF RATES UNDER VARIOUS CONDITIONS

At first, it was confirmed that there was linearity between the total amount of water supply \((R+I)\) and the runoff. In this case, the gradient of the line can be equal to the runoff coefficient \((O/(R+I))\).

By the above evaluation method we calculated the runoff coefficients and arranged them as shown in Table 3 and Figure 4.

In Table 3, they are divided into two season (main and off season), and we divided them into three cases for each season as follows: (i) the case of runoff in the whole period, (ii) the case of increasing water depth fluctuation \((dH>0 \text{ mm/day})\) and (iii) decreasing water depth fluctuation \((dH\leq0 \text{ mm/day})\) while the runoff responded to rainfall and irrigation \((R+I, O>0 \text{ mm/day})\).

From the results of the above calculations we can say the following:

1) The average daily runoff coefficient is 69% in the off season and 66% in the main season. These values are somewhat lower than those cited in the previous chapter (70.7% in the off
season, 61.1% in the main season) because of the different calculation method. Therefore, the runoff coefficient was estimated as the average of the two figures as follows: 70% in the off season and 64% in the main season.

2) Usually the runoff coefficients are higher when the water depth is decreasing than when it is increasing. This shows that there is nonlinearity in the relationship between detention and runoff in the paddy field, which might be affected by the detention acting upon the cracks.

Figure 5 shows the relationship between the fluctuation of water depth and the runoff at the various water depths in the paddy field.

In the case of decreasing water depth fluctuation \((dh\leq 0 \text{ mm/day})\), the runoff amount to the water depth fluctuation was larger in the dried field condition than in the submerged field condition. In the case of increasing water depth fluctuation \((dh>0 \text{ mm/day})\), the greater the water depth brought about, the larger the gradient became.

From the above results we can say the following:

1) In the case of decreasing water depth fluctuation, cracks inside paddy fields (including borders (batas)) might affect the runoff.

2) In the case of increasing water depth fluctuation, overflow from border (batas) might affect the runoff, because in this area flood irrigation is adopted generally.

3) In general, when the water depth inside the paddy fields is kept at from a few cm to 10 cm, the gradient between water depth fluctuation and runoff is minimized.

For rice cultivation, suitable water depth seems to be around 5 to 7.5 cm, but the maximum 10 cm gives consideration to both the growth of rice and the control of weeds.

It can however be said that 5 to 7.5 cm water depth is suitable practically from both the stand points of both growth of rice and reducing runoff amounts.

When average water depth is kept at from 5 cm to 7.5 cm, the runoff coefficient can be calculated as 0.63 \((r=0.95, n=13)\). This value is decreased around 10% from the present runoff coefficient.

The correlation coefficients in each case are shown in Table 4-1 and 4-2 using multiple regression analyses.

From Table 4-1 the following can be pointed out:

### Table 3  Runoff-coefficients

<table>
<thead>
<tr>
<th></th>
<th>Off season</th>
<th></th>
<th>Main season</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Runoff-coefficient</td>
<td>Correlation coefficient</td>
<td>Number of data</td>
</tr>
<tr>
<td>Whole</td>
<td></td>
<td>0.69</td>
<td>0.80</td>
<td>0.66</td>
</tr>
<tr>
<td>(dh&gt;0)</td>
<td></td>
<td>0.79</td>
<td>0.98</td>
<td>0.74</td>
</tr>
<tr>
<td>(dh\leq 0)</td>
<td></td>
<td>0.92</td>
<td>0.82</td>
<td>0.89</td>
</tr>
<tr>
<td>Presaturation</td>
<td></td>
<td>0.60</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Except Presaturation</td>
<td></td>
<td>0.73</td>
<td>0.84</td>
<td></td>
</tr>
</tbody>
</table>

*Irrigation Engineering and Rural Planning No. 4, 1983*
1) Between \((R+I)\) and \(O\) in both seasons high correlation coefficients were found (off season 0.982, main season 0.977).

2) The correlation coefficients between \((R+I)\) and \(dH\) were also high (off season 0.802, main season 0.886).

Figure 4-1; Relationship between Water Supply \((R+I)\) and Runoff \(O\) in each case

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3) High correlation coefficients were also found between $O$ and $dH$ in both seasons (off season 0.692, main season 0.772).

These results show that in general larger water supply brings about more runoff and increase in $dH$. From this fact the investigation of suitable water depth is important for water management.

From Table 4-2 we can find the following:

*Figure 4-2; Relationship between Water Supply (R+I) and Runoff (O) in each case*
water depth decreasing

\[ 
\begin{align*}
\text{Runoff} & \quad \text{mm/d} \\
-272 \text{mm} < H \leq -179 \text{mm} & \quad \bullet \\
101 \text{mm} < H < 106 \text{mm} & \quad \bullet \\
122 \text{mm} < H < 109 \text{mm} & \quad \bullet \\
36 \text{mm} < H < 103 \text{mm} & \quad \bullet
\end{align*}
\]

water depth increasing

fluctuation of water depth \((dH_{\text{mm/d}})\)

\[ 
\begin{align*}
\text{decrease} & \quad \text{increase}
\end{align*}
\]

**Figure 5** Relationship between the fluctuation of water depth and the runoff under various water depths in the paddy field. (off season, 1980)

**Table 4-1** Correlation matrices \((RZI, \sigma > 0 \text{ mmday}, dH > 0 \text{ mmday})\)

*Off season (Mar. 21 to Sept. 9 1980)*

<table>
<thead>
<tr>
<th></th>
<th>(RZI)</th>
<th>(E.T)</th>
<th>(dH)</th>
<th>(O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(RZI)</td>
<td>1.0000</td>
<td>-0.4140</td>
<td>0.8022</td>
<td>0.9819</td>
</tr>
<tr>
<td>(E.T)</td>
<td>-0.4140</td>
<td>1.0000</td>
<td>-0.6136</td>
<td>-0.4103</td>
</tr>
<tr>
<td>(dH)</td>
<td>0.8022</td>
<td>-0.6136</td>
<td>1.0000</td>
<td>0.6924</td>
</tr>
<tr>
<td>(O)</td>
<td>0.9819</td>
<td>-0.4103</td>
<td>0.6924</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

*Main season (Sept. 21 1980 to Feb. 27 1981)*

<table>
<thead>
<tr>
<th></th>
<th>(RZI)</th>
<th>(E.T)</th>
<th>(dH)</th>
<th>(O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(RZI)</td>
<td>1.0000</td>
<td>-0.0819</td>
<td>0.8855</td>
<td>0.9767</td>
</tr>
<tr>
<td>(E.T)</td>
<td>-0.0819</td>
<td>1.0000</td>
<td>0.0206</td>
<td>-0.1969</td>
</tr>
<tr>
<td>(dH)</td>
<td>0.8855</td>
<td>0.0206</td>
<td>1.0000</td>
<td>0.7723</td>
</tr>
<tr>
<td>(O)</td>
<td>0.9767</td>
<td>-0.1969</td>
<td>0.7723</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

\((RZI)=OZE.TZdH\)

*Irrigation Engineering and Rural Planning No. 4, 1983*
1) There are high correlation coefficients between \((R+I)\) and \(O\) (0.813 in the off season, 0.906 in the main season).

2) The influences of \(E.T.\) and \(dH\) on other terms in the main season are larger than those in the off season, excepting the relationship between \(dH\) and \(O\) in the off season.

Finally, it is naturally said that in both seasons the influence of water supply is larger in the case of \(dH > 0\) mm/day than in the case of \(dH \leq 0\) mm/day, but that the influences for \(E.T.\) in the main season are inversely related.

V. CONCLUSIONS

Finally we can summarize the followings as our conclusions:

1) Seasonal total water supply \((R+I)\) was 1594 mm in the off season and 1394.5 mm in the main season (14.3\% less than in the off season).

2) In both seasons, about 60\% of the total water supply depended upon rainfall and about 40\% upon irrigation water. (The degree of the dependency of water supply on irrigation water was slightly higher in the main season.)

3) The total consumptive use \((E.T.)\) was 801 mm in the off season and 818.3 mm in the main season. The values were almost equal. As the duration of the off season was 173 days and that of the main season 160 days, the daily consumptive use \((E.T.)\) in the off season (4.63 mm/day) was less than that in the main season (5.11 mm/day).

4) The total runoff was 1127.3 mm in the off season, about 30\% larger than that (852.8 mm) in the main season. This was mainly caused by the runoff in the presaturation.

5) The ratio of the total consumptive use \((E.T.)\) to the total water supply was 50.3\% in the off season and 58.7\% in the main season.

6) The ratio of the total runoff to the total water supply was about 70\% in the off season and about 64\% in the main season.

7) Generally in both seasons a large water supply brought about more runoff. This shows that investigation of suitable water depth is necessary for water management.

8) The runoff increased suddenly when water depth in the paddy field was over 10 cm. This shows that suitable maintenance of the borders \(batas\) is important for water management using borders.

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9) It is important for reasonable irrigation water management to maintain the borders (batas) and to keep suitable water depth (from a few to 10 cm) from the viewpoint of rice cultivation and runoff water. When average water depth is between 5 cm and 7.5 cm, the runoff coefficient can be improved to 63%, which shows a decrease in runoff of around 10% over the present runoff coefficient. In addition, good maintenance of borders (batas) may decrease the runoff by around 20% in total.

10) In the case of the water balance for the whole ACRBD 4, it is sufficient to conceive the terms of \( R || I \), \( O \), \( E. T. \) and \( dH \), but for dynamic hydraulic analyses, for example, simulation analyses of the flow direction and the velocity between paddy fields, it may be necessary to take into account underground water too. It might also be necessary for the dynamic hydraulic analyses to separate percolation and surface runoff from \( O \) (runoff).

At the end of this report, we want to express our appreciation for the great cooperation of Dato' Syed Ahmad Almahdali, General Manager, and his staff officers in MADA (Muda Agricultural Development Authority).

This report was written during the stay of all the authors in Malaysia (June 3 1981 to April 23 1982).