Effects of Soil Clay Content on Water Balance and Productivity in Rainfed Lowland Rice Ecosystem in Northeast Thailand

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Abstract: Water availability is one of the determinants of productivity of rainfed lowland rice (Oryza sativa L.). Quantifying water losses from a paddy field, such as deep percolation and lateral seepage, assists estimation of water availability to the rice crop and development of appropriate water management in the lowlands. The main objective of this study was to evaluate paddy water availability and productivity across various soils in Northeast Thailand. The daily rate of downward water flow from standing water in the field (D) varied between 0 and 3 mm day−1 from clayey to sandy soils when the standing water was connected to groundwater table. However, when the standing water was separated from groundwater table, D increased up to 5 mm day−1 on soils with very low clay content in the topsoil. Daily net lateral water flow from the field (L) averaged over the season varied between 5 and 24 mm day−1 for the outflow and between 3 and 16 mm day−1 for the inflow. Both the inflow and outflow tended to be associated negatively with the soil clay content. The seasonal water loss through D plus L during the growing season in the lowlands was also negatively related to the soil clay content. The yield of a major rainfed lowland rice cultivar in Northeast Thailand (KDML105) varied from 2 to 4 t ha−1 across the region, and the water productivity (the ratio of grain yield to cumulative rainfall from transplanting/seedling establishment to maturity) ranged from 3 to 9 kg ha−1 mm−1. High clay soils could provide good standing water until late in the growing season, so the high production efficiency was measured on such soils.

Key words: Oryza sativa, Paddy, Percolation, Seepage, Water table.

Late season drought in rainfed lowland rice (Oryza sativa L.) growing areas is common in Northeast Thailand, and the drought often has a severe negative effect on the yield of late flowering cultivars (Cooper et al., 1999). The yield is remarkably reduced when standing water in the lowland field disappears before flowering time (Jearakongman et al., 1995). Several studies have shown large genotypic variations in yield response to different water availability in rainfed lowland rice in drought-prone environments (Cooper et al., 1999; Pantuwan et al., 2002). The yield variations are often explained by paddy water availability (e.g. standing water) during the growing season, particularly flowering time (Ouk et al., 2006). A quantitative analysis of water loss from the lowland field is therefore useful in understanding plant water availability and its effect on genotypic performance. However, few detailed studies have been reported on the effect of paddy water availability on rice productivity in Northeast Thailand (e.g. Sharma et al., 1995; Homma et al., 2003).

Most of rice paddy fields in the study region lie on gently sloping land, and rice is grown on various types of soils. Information on the downward and lateral water movement is available for irrigated rice, but it is sparse in rainfed lowland rice ecosystems, where the spatial heterogeneity is larger than in irrigated rice systems and may lead to large variations in those water movements from paddy to paddy. Soil texture, particularly clay content, is the primary factor in determining the downward water loss from the lowland field (Tsubo et al., 2005), such that it could determine the water productivity of rainfed lowland rice.

Quantifying each component of the paddy water balance under rainfed lowland conditions on a wide range of soils can help to understand large variation in rice productivity in Northeast Thailand. This would therefore assist to improve selection criteria for cultivar/line candidates of drought resistance, and agronomic management such as time of planting, direct seeding and fertiliser management, in the region. The work reported here is extension of our previous study (Tsubo et al., 2005), aiming to examine variations in water availability and productivity across the lowlands of different soil types. Retention of soil water is greater in clayey than sandy soils, so high crop productivity is expected when grown on fine-textured, clayey soils under rainfed conditions. The specific objectives of the present study were therefore...
Table 1. Soil (the topsoil of 200 mm depth) and agronomic information of the experimental sites.

| Location     | Site | Paddy Field | Soil texture (%) | Cultural practice | Treatment                     | Seeding   | Transplanting |
|--------------|------|-------------|------------------|-------------------|-------------------------------|-----------|---------------|
|              |      |             | Clay  Silt  Sand | Type              | Cultivar  Planting*           |           |               |
|              |      |             | %      %      % |                   |                               |           |               |
|              |      |             | Condition       | Soil texture (%)  | Cultural practice             |           |               |
|              |      |             | On-station      | Clay  Silt  Sand  | Treatment                     |           |               |
|              |      |             | On-farm         | 9     12     79  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 9     12     79  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 11    15     74  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 8     14     78  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 8     14     78  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 8     14     78  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 8     14     78  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 21    18     61  | Sandy clay loam               |           |               |
|              |      |             | On-farm         | 4     7      88  | Loamy sand                    |           |               |
|              |      |             | On-farm         | 4     7      88  | Loamy sand                    |           |               |
|              |      |             | On-farm         | 5     20     75  | Sandy loam                    |           |               |
|              |      |             | On-farm         | 5     20     75  | Sandy loam                    |           |               |
|              |      |             |                 |                   |                               |           |               |
| Chum Phae    | A    | On-station  | 30     30     40 | Clay loam          | KDML105  TP                      | Low fertilizer | 7-Jul | 3-Aug         |
|              | 2    | On-station  | 30     30     40 | Clay loam          | KDML105  TP                      | High fertilizer | 7-Jul | 3-Aug         |
|              | B    | On-farm    | 9      12     79 | Sandy loam         | IR62266  DS                      | Low fertilizer | 27-Jul | -             |
|              | 2    | On-farm    | 9      12     79 | Sandy loam         | IR62266  DS                      | High fertilizer | 27-Jul | -             |
| Khon Kaen    | -    | On-station | 11     26     63 | Sandy loam         | KDML105  TP                      | Early transplanting | 22-Jun | 27-Jul       |
|              | -    | On-station | 13     25     62 | Sandy loam         | KDML105  TP                      | Late transplanting | 27-Jul | 5-Sep         |
| Phimai       | A    | On-station | 47     22     31 | Clay               | KDML105  TP                      | Low fertilizer | 3-Jul  | 1-Aug         |
|              | 2    | On-station | 47     22     31 | Clay               | KDML105  TP                      | High fertilizer | 22-Jul | 9-Aug         |
|              | B    | On-station | 11     15     74 | Sandy loam         | NSG19    DS                       | -            | 11-Aug | -             |
|              | 2    | On-station | 11     15     74 | Sandy loam         | IR58821  DS                       | -            | 11-Aug | -             |
| Surin        | -    | On-station | 8      14     78 | Sandy loam         | KDML105  DS                      | Straw mulching | 20-Jul | -             |
|              | -    | On-station | 8      14     78 | Sandy loam         | KDML105  TP                      | Fertilizer with urea | 23-Jun | 28-Jul       |
|              | -    | On-station | 8      14     78 | Sandy loam         | KDML105  TP                      | Compost      | 23-Jun | 31-Jul        |
|              | -    | On-station | 8      14     78 | Sandy loam         | KDML105  TP                      | Fertilizer    | 14-Jun | 20-Jul        |
| Ta Pra       | -    | On-farm    | 15     28     57 | Sandy loam         | RD6      TP                       | High Toposequence | 16-Jun | 26-Jul       |
|              | -    | On-farm    | 21     18     61 | Sandy clay loam    | RD6      TP                       | Low Toposequence | 16-Jun | 26-Jul       |
| Ubon Ratchathani | A  | On-station | 4      7      88 | Loamy sand         | KDML105  TP                       | -            | 4-Jul  | 28-Jul        |
|              | 2    | On-station | 4      7      88 | Loamy sand         | KDML105  DS                       | -            | 4-Jul  | -             |
|              | B    | On-farm    | 5      20     75 | Sandy loam         | NSG19    DS                       | -            | 25-Jul | -             |
|              | 2    | On-farm    | 5      20     75 | Sandy loam         | IR58821  DS                       | -            | 25-Jul | -             |

*TP: transplanting, DS: direct seeding.
to evaluate relationships between components of the water balance and clay content of the topsoil on a wide range of soils and to indicate the importance of the textural content of soil on rainfed lowland rice production.

Materials and Methods

1. Experiments

The field experiments were carried out under rainfed conditions at six locations (Chum Phae, Khon Kaen, Phimai, Surin, Ta Pra and Ubon Ratchathani) in Northeast Thailand during the 2000 wet season (Table 1). Most of the experiments were conducted under on-station conditions except the Chum Phae-Site B and Ubon Ratchathani-Site B experiments (on-farm experiments). The on-farm field was located at high altitude relative to the on-station field, but the fields were not in the same toposequences. The stations’ fields were relatively flat. The Paddy 1 and Paddy 2 at the Ta Pra experimental site were located at high and low positions, respectively, in a toposequence. The field conditions were similar to on-farm conditions. The site was approximately 15 km away from the Khon Kaen on-station site.

Two or four paddy fields were selected within each location, totalling 20 paddy fields covering a wide range of cultural practices of rainfed lowland rice. All the paddy fields were situated on a gentle slope (1-3%). The paddy fields had hardpans at 150-250 mm below the soil surface. The topsoil (200 mm depth) was sampled at each location, and there was large variation in the textural content of the soils across locations (Table 1). The experiments at Phimai and Chum Phae were conducted on two distinct soils. Concerning soil physical properties, for reference, Pannangpetch and Vorasoot (2005) reported a bulk density of 1.5 g cm⁻³, a field capacity of 23.6 % and a wilting point of 16.5 % for the 0-10 cm layer of a loam soil in Khon Kaen, and Sharma et al. (1995) reported 1.5-1.6 g cm⁻³, 11.4 % and 3.3 %, respectively for the 0-40 cm layer of a loamy sand soil in Ubon Ratchathani.

The paddies were cultivated by different cultural practices (i.e. different cultivars, transplanting (TP)/direct seeding (DS), fertilizer application rates), as shown in Table 1. KDML105 and RD6 are major rice cultivars in rainfed lowlands in Northeast Thailand, and NSG19 has a high degree of drought tolerance under rainfed lowland conditions (Cooper et al., 1999). IR62206 and IR58821 are promising populations. Rice was seeded in mid June to late July, and the plants were transplanted in late July to early August (except Khon Kaen-Paddy 2) unless direct seeding was practiced (Table 1). The plants flowered in mid to late October and matured in mid to late November.

2. Measurements and computations

The apparatuses used to determine components of the water balance in the present work are described in detail by Tsubo et al. (2005), so a brief description of the apparatuses is given here. The downward water movement was measured using the percolator, a steel cylindrical tube with a lid to prevent evaporation loss and rainfall entering the tube. Free water levels above the hardpan (perched water table) were measured using a short PVC tube (perched water tube). The perched water tube was installed to a depth of 200-250 mm below the soil surface near the bund in the field. Groundwater levels were measured using a 2-m long PVC tube. Using a soil auger, the groundwater tube was installed in the bund to prevent the leakage of the field surface water along the side of the tube. All measurements were taken on a daily basis. Daily rainfall data was collected at each location. Grain yield (GY) was measured at maturity, and water productivity (WP) with respect to water input (rainfall) and evapotranspiration (WP ET) respectively was determined as follows:

\[ WP_{WI} = \frac{GY}{\Sigma R} \]  
and  
\[ WP_{ET} = \frac{GY}{\Sigma ET} \]

where \( \Sigma R \) and \( \Sigma ET \) are the total amounts of rainfall and evapotranspiration, respectively, from transplanting to maturity, and for the direct seeding treatment it is considered as the total amounts from seedling establishment (one month after seeding) to maturity.

The daily rate of downward water movement (D) from soil surface through the hardpan was determined when standing water was present in the field, from the rate of change of free water level within the percolator during the period that did not include heavy rain days (Tsubo et al., 2005). Assuming that all transpiration water comes from soils above the hardpan because most of the root system exists in the topsoil layer, the daily rate of net lateral water movement (L) was computed for the period from transplanting/seedling establishment to maturity (2 to 4 months; Table 1) using the water balance equation:

\[ L = R - D - ET - AS \]

where \( R \), \( ET \) and \( AS \) are rainfall (measured), evapotranspiration from the paddy field, and the change in field water level (measured), respectively (all in mm day⁻¹). ET was estimated using the FAO crop coefficient approach (Allen et al., 1998), and the Priestly and Taylor (1972) equation was used to estimate the reference ET. The crop coefficient was assumed to be 1.05 at transplanting/seedling establishment and to increase linearly up to 1.20 at flowering (Allen et al., 1998). It was fixed at 1.20 during the period from flowering to maturity. In the case where the perched water disappeared (i.e.
no free water in the topsoil), ET was assumed to be nil. This occurred mostly late in the growing season. When standing water disappeared from the field, the change in amount of soil water was estimated using soil porosity (Tsubo et al., 2006): 0.4, 0.45 and 0.5 for sandy, loamy and clayey soils, respectively. The total amount of D plus L (D+L) was then calculated by the difference using the water balance model. The D+L was disaggregated into the two components using the ratio of D+L to D (seepage ratio) determined when standing water was present in the field. When D+L was less than zero (i.e. net water gain), D+L was regarded as only L assuming D = 0. When no perched water table was observed, both D and L were assumed to be zero. When data of the D measurement was not available (Paddy 2 at Chum Phae-Site 2 and Phimai-Site 1), L was calculated assuming that D for Paddy 2 is equal to D for Paddy 1 at the same site. At Ubon Ratchathani-Site 1-Paddy 2, deep groundwater table was observed throughout the growing season, so D determined when separate perched water was developed, was employed to compute L.

**Results**

1. **Perched water and groundwater**

Standing water disappeared from the field in late October to mid November at Chum Phae, Khon Kaen, Surin, Ta Pra and Ubon Ratchathani. For example, disappearance of the standing water began in late October at Chum Phae-Site A-Paddy 1 (Fig. 1a) and in mid November at Surin-Paddy 4 (Fig. 1b). At Phimai, the standing water remained until late November. The proportion of the period from transplanting/seedling establishment to the day when the standing water disappeared was relatively great in low clay soils, e.g. Chum Phae-Site B compared with the Site A (Table...
| Location      | Site | Paddy from TP/SE to maturity | Days Standing water | Downward water flow rate (mm day\(^{-1}\)) | Lateral water movement | Inflow |
|---------------|------|-------------------------------|---------------------|---------------------------------------------|------------------------|--------|
|               |      |                               | Days with no water | Fraction of growing season | Rate (mm day\(^{-1}\)) | Fraction\(^{d}\) | Rate (mm day\(^{-1}\)) | Fraction\(^{d}\) |
| Chum Phae     | A    | 1                             | 107                 | 20                            | 0.19                   | 0.4                | 10.3                             | 11.8 | 0.42 | 7.2  | 11.0 | 0.46 |
|               |      | 2                             | 108                 | 18                            | 0.17                   | 0.7                | 10.6                             | 15.1 | 0.32 | 4.7  | 5.7  | 0.56 |
|               | B    | 1                             | 110                 | 66                            | 0.60                   | 0.0                | 5.7                              | 8.4  | 0.46 | 8.2  | 13.6 | 0.37 |
|               |      | 2                             | 111                 | 110                           | 0.99                   | na                 | 10.0                             | 14.7 | 0.25 | 4.5  | 4.5  | 0.50 |
| Khon Kaen     | -    | 1                             | 105                 | 28                            | 0.27                   | 1.3                | 15.8                             | 16.7 | 0.42 | 9.2  | 19.1 | 0.50 |
|               |      | 2                             | 88                  | 33                            | 0.38                   | 0.5                | 13.6                             | 21.5 | 0.34 | 4.7  | 7.3  | 0.47 |
| Phimai        | A    | 1                             | 106                 | 0                             | 0.00                   | 0.2                | 16.1                             | 11.4 | 0.37 | 10.7 | 11.4 | 0.63 |
|               |      | 2                             | 99                  | 0                             | 0.00                   | na                | 10.6                             | 13.5 | 0.37 | 9.3  | 10.5 | 0.63 |
|               | B    | 1                             | 52                  | 0                             | 0.00                   | 0.8                | 6.7                              | 7.7  | 0.32 | 3.1  | 2.6  | 0.68 |
|               |      | 2                             | 83                  | 14                            | 0.17                   | 0.5                | 4.7                              | 7.2  | 0.45 | 3.3  | 3.6  | 0.51 |
| Surin         | -    | 1                             | 97                  | 23                            | 0.24                   | 1.1                | 20.5                             | 35.0 | 0.56 | 8.8  | 17.9 | 0.47 |
|               |      | 2                             | 116                 | 32                            | 0.28                   | 1.0                | 19.2                             | 32.5 | 0.31 | 7.7  | 24.6 | 0.54 |
|               | -    | 3                             | 110                 | 22                            | 0.20                   | 1.2                | 21.5                             | 32.6 | 0.41 | 14.0 | 28.9 | 0.48 |
|               | -    | 4                             | 116                 | 1                             | 0.01                   | 0.8 (3.4)          | 23.8                             | 29.1 | 0.37 | 11.3 | 27.0 | 0.63 |
| Ta Pra        | -    | 1                             | 113                 | 30                            | 0.27                   | 3.3                | 8.6                              | 21.8 | 0.41 | 6.3  | 4.1  | 0.51 |
|               |      | 2                             | 113                 | 33                            | 0.29                   | 0.0                | 22.8                             | 34.7 | 0.31 | 7.3  | 8.6  | 0.59 |
| Ubon Ratchathani |  A | 1                             | 104                 | 9                             | 0.09                   | 1.9                | 17.4                             | 18.1 | 0.48 | 14.4 | 15.4 | 0.52 |
|               |      | 2                             | 105                 | 77                            | 0.73                   | na (5.1)           | 17.8                             | 23.5 | 0.39 | 13.7 | 25.0 | 0.40 |
|               | B    | 1                             | 68                  | 45                            | 0.66                   | 1.4                | 19.3                             | 19.7 | 0.40 | 7.8  | 12.7 | 0.57 |
|               |      | 2                             | 98                  | 75                            | 0.77                   | 3.5                | 18.2                             | 18.1 | 0.34 | 13.6 | 26.1 | 0.33 |

\(^{a}\)TP/SE: transplanting or seeding establishment (for direct seeding).

\(^{b}\)na: not available. The values in brackets D determined when Separate perched water and groundwater tables were present in the field.

\(^{c}\)The outflow and inflow were averaged over the period from TP/SE to maturity using only data of the water loss and gain, respectively, when standing water was present in the field. It was assumed that the downward water flow for Paddy 2 at Chum Phae-Site B and Phimai-Site A is equal to that for Paddy 1 at the same sites for the L computations.

\(^{d}\)The number of days with net outflow or net inflow was divided by the total number of days from TP/SE to maturity.
The standing water was mostly less than 100 to 150 mm throughout the season, although the depth of the standing water increased considerably as heavy rain events occurred. Separate perched water and groundwater tables were observed from the vegetative stage at Ubon Ratchathani (Fig. 1c) and late in the season at Surin (Fig. 1b), while the other four locations (Chum Phae, Khon Kaen, Phimai and Ta Pra) showed similar free water levels in perched water and groundwater tubes, indicating that there was mostly only one water table throughout the growing season.

2. **Downward water flow**

The highest mean D value was observed at Ubon Ratchathani (2.3 mm day$^{-1}$ ranging between 1.4 and 3.5 mm day$^{-1}$). The fields at Ta Pra had a large downward water movement at the high toposequence and no downward water movement at the low toposequence position (Table 2). Mean D values for the other locations ranged between 0 and 1.3 mm day$^{-1}$. As shown in Figs. 1b and 1c, there was no difference in D between periods when readings of the groundwater tube were above the hardpan, but D increased after groundwater level declined below the hardpan. For example, at Ubon Ratchathani (Fig. 1c), D for Paddy 1 increased from 1.3 mm day$^{-1}$ to 2.4 mm day$^{-1}$ with groundwater level decreasing to −233 mm (the mean value during the period of 11–29 October). In another rice paddy field (Paddy 2) at the same site, D increased to 5.1 mm day$^{-1}$ with a groundwater level decreasing to −446 mm. This phenomenon of high D with low groundwater table was observed in only sandy, coarse-textured soils.

In sandy soils, there is a large positive effect of puddling intensity on the hardpan formation, by which the downward water movement is determined mostly. Puddling intensity varies from field to field in farmland; some are well-puddled and others are not. The soils of the on-farm fields concerned consist of high sand content, and puddling practice is not similar between on-farm and on-station conditions. Thus, only the data collected from the fields under on-station conditions was used to establish a relationship of D with clay content of the topsoil. Also, the data from Phimai-Site B was not used since the site was planted with different cultivars by direct seeding. Fig. 2 shows a negative relationship between D (when groundwater level was above the hardpan) and the clay content. The negative association was evident as there was large water loss through D in soils with low clay content. When the data collected from the fields under on-farm conditions was included, a good correlation of D with the clay content could not be seen because of a large variation in the values of D.

3. **Net lateral water flow**

There was large variation in L during the growing season, and this was often associated with rainfall events. In the present study, daily L was categorised into three different flows: net lateral inflow (i.e. L < 0), net lateral outflow (i.e. L > 0) and no lateral flow (i.e. L = 0). The maximum daily outflow and inflow varied across the locations, ranging from 24 to 152...
Table 3. The water budget of the rainfed lowland fields during the period from transplanting/seedling establishment to maturity, and grain yield and water productivity.

| Location         | Site | Paddy | Rainfall (mm) | Evapo-transpiration (mm) | Downward water flow (mm) | Net lateral water flow (mm) | ∆S (mm) | R/ET | Grain yield (kg ha\(^{-1}\)) | Water productivity based on rainfall (kg ha\(^{-1}\) mm\(^{-1}\)) | Water productivity based on ET (kg ha\(^{-1}\) mm\(^{-1}\)) |
|------------------|------|-------|---------------|--------------------------|--------------------------|-----------------------------|---------|------|----------------------------|-------------------------------------------------|--------------------------------------------------|
| Chum Phae        |      |       |               |                          |                          |                             |         |      |                            |                                                 |                                                  |
|                 | A    | 1     | 435           | 501                      | 37                       | 112                         | -215   | 0.87 | 2631                       | 6.0                                             | 5.3                                               |
|                 |      | 2     | 435           | 501                      | 66                       | 80                          | -212   | 0.87 | 3946                       | 9.1                                             | 7.9                                               |
|                 | B    | 1     | 374           | 465                      | 0                        | -42                         | -49    | 0.80 | 243                        | 0.6                                             | 0.5                                               |
|                 |      | 2     | 374           | 428                      | 0                        | 23                          | -77    | 0.87 | 1343                       | 3.6                                             | 3.1                                               |
| Khon Kaen        |      | 1     | 680           | 505                      | 111                       | 211                         | -147   | 1.35 | 2504                       | 3.7                                             | 5.0                                               |
|                 |      | 2     | 277           | 359                      | 31                       | 208                         | -321   | 0.77 | 1898                       | 6.9                                             | 5.3                                               |
| Phimai           |      | 1     | 511           | 513                      | 21                       | -98                         | 75     | 1.00 | 3040                       | 5.9                                             | 5.9                                               |
|                 |      | 2     | 477           | 470                      | 19                       | -185                        | 173    | 1.01 | 3760                       | 7.9                                             | 8.0                                               |
|                 | B    | 1     | 180           | 237                      | 40                       | 4                           | -101   | 0.76 | 2920                       | 16.2                                            | 12.3                                              |
|                 |      | 2     | 180           | 384                      | 41                       | 39                          | -284   | 0.47 | 1070                       | 5.9                                             | 2.8                                               |
| Surin            |      | 1     | 596           | 367                      | 84                       | 300                         | -155   | 1.62 | 2913                       | 4.9                                             | 7.9                                               |
|                 |      | 2     | 755           | 488                      | 86                       | 212                         | -51    | 1.55 | 3684                       | 4.9                                             | 7.5                                               |
|                 |      | 3     | 751           | 482                      | 112                      | 239                         | -82    | 1.56 | 3140                       | 4.2                                             | 6.5                                               |
|                 |      | 4     | 777           | 562                      | 92                       | 170                         | -47    | 1.38 | 2064                       | 3.4                                             | 4.7                                               |
| Ta Pra           |      | 1     | 732           | 549                      | 395                      | 38                          | -160   | 1.33 | 3304                       | 4.5                                             | 6.0                                               |
|                 |      | 2     | 732           | 535                      | 0                        | 296                         | -99    | 1.37 | 1910                       | 2.6                                             | 3.6                                               |
| Ubon Ratchathani| A    | 1     | 660           | 502                      | 184                       | 84                          | -110   | 1.31 | 2709                       | 4.1                                             | 5.4                                               |
|                 |      | 2     | 653           | 398                      | 208                      | 168                         | -121   | 1.64 | 2874                       | 4.4                                             | 7.2                                               |
|                 | B    | 1     | 361           | 295                      | 48                       | 224                         | -206   | 1.22 | 2500                       | 6.9                                             | 8.5                                               |
|                 |      | 2     | 361           | 295                      | 130                      | 167                         | -231   | 1.22 | 3230                       | 8.9                                             | 10.9                                              |

∆S: the change in water level, R/ET: the ratio of rainfall to evapotranspiration (the aridity index).
mm day⁻¹ for the outflow and from 13 to 192 mm day⁻¹ for the inflow. The daily rate of the outflow averaged over the growing season was greater than the inflow in all the paddy fields except Chum Phae-Site B-Paddy 1, and the outflow varied greatly across the paddies compared with the inflow (Table 2). At Ta Pra, there was no difference in the inflow between the high and low toposequence positions, but the outflow was much larger at the low landscape. The large outflow at the low position might result from the accumulation of lateral water from upper paddy fields. At Phimai, both the outflow and inflow were observed to be lower in the low clay soil than the high clay soil.

4. Seasonal water budget

There were large variations in the seasonal amounts in D and L across the locations, but not ET (Table 3). The ratio of rainfall to ET (R/ET; the aridity index) for Chum Phae was lower than one (on average R/ET = 0.9), so the fields were potentially dried out late in the growing season only by ET. At Khon Kaen, the ET plus D+L loss was greater than rainfall received during the period, resulting in the late season drought. The fields at Phimai, particularly at the Site A, lost water through ET which was equal to rainfall received during the period (R/ET = 1.0), and the fields gained much water through L. Thus, the fields sustained standing water until the end of the season. At Surin, the fields lost much water through D+L, but had very high rainfall input to the fields (R/ET = 1.5). Thus, the sufficient amount of rainfall kept standing water in the fields until crop maturity. Both D+L and R/ET at Ubon Ratchathani were as high as those at Surin, but the former fields received lower rainfall than the latter fields. Hence, standing water disappeared from the fields earlier in the season at Ubon Ratchathani.

5. Relationships of water availability and productivity with clay content

Puddling intensity affects the downward water movement, as mentioned above. This then influences the L computation, which is estimated from the water balance equation (Eq. 2). Therefore, only the data collected from the fields under on-station conditions was used to establish a relationship of L with clay content of the topsoil. A negative relationship between seasonal mean L and clay content of the topsoil was found for those fields (Fig. 3), as a similar trend was found for the daily rate of the downward water movement (Fig. 2). This indicates that the soil clay content could be a good index of paddy water availability, to which both the downward and lateral water losses contributed negatively.

The grain yield (GY) varied from 250 to 3950 kg ha⁻¹ across the locations in association with large variation in WP from paddy to paddy (Table 3). Because some of the paddies were cultivated with cultivars other than KDML105, only the data for KDML105 was used to depict a relationship between the productivity and the clay content. Chum Phae and Phimai (high clay content of the soils) on average produced higher GY than Khon Kaen, Surin and Ubon Ratchathani.
(low clay content). WP<sub>w1</sub> for Khon Kaen, Surin and Ubon Ratchathani was relatively low since low water availability affected yield greatly. Thus, high efficiency of rainwater use for GY tended to be associated with high clay content of the topsoil, so the water availability and then the rice productivity in the study region could be explained largely by the clay content (Fig. 4). Interestingly, WP<sub>e1</sub> was not dependent on the clay content, while WP<sub>w1</sub> was correlated with the clay content. This indicates that better retention of soil water was the major reason for greater WP<sub>w1</sub> under clayey soils.

**Discussion**

The perched water level (or standing water layer in the field) is influenced by the local (field level) hydraulic properties, while groundwater table level reflects the regional (surrounding environment) conditions. When the perched water level is higher than the groundwater table, water from the field flows downward, recharging the groundwater. Vice versa, when the groundwater is higher than the perched water, water may move upward. If the recharge from the field is faster than decrease in groundwater level (which is influenced by the regional hydrology and the hydraulic conductivity of the subsoil), perched water table can be "connected" to the groundwater, and the measured decrease in water level may reflect the overall decline in general regional groundwater. On the other hand, if the recharge from the field (e.g. effected by hard pan, compaction) is lower than the decrease in groundwater table (e.g. fast decline due to high conductivity of subsoil, sandy), there is a separation between perched water and groundwater.

The mean D value at Ubon Ratchathani, which was determined when one continuous water table was observed at different soil depths, was less than a half the value for the same area reported by Fukai et al. (1995) and Sharma et al. (1995) (6.0 and 6.3 mm day<sup>-1</sup>, respectively). However, D determined when separate perched water and groundwater tables were observed (5.1 mm day<sup>-1</sup>) was similar to the reported values. Therefore, among the lowland fields with standing water and one continuous water table, those with low clay content maintain low D, whereas the lowland field that tends to have separate perched water and groundwater tables has high D (Bouman et al., 2001). There is little effect of puddling on D on clayey soils (Sharma and De Datta, 1986), so the (saturated) hydraulic conductivity of the topsoil can be similar to that of the subsoil, resulting in no separate groundwater table below the hardpan. On sandy soils, puddling reduces permeability of the hardpan (Sharma and De Datta, 1986), implying that an unsaturated layer is easily developed below the hardpan. So, when perched water is developed, water flow from the topsoil (the saturated layer) to the subsoil (the unsaturated soil) may increase with decrease in groundwater level. In the present study, the development of separate deep groundwater table was indeed observed on coarse textured soils with low clay content (Ubon Ratchathani and Surin), and relatively large D was measured in such field conditions.

The downward water flow (D) is significantly lower on sandy, coarse-textured soils compacted by a heavy machine, but little compaction effect can be found.
on the total water use (D, L plus ET) (Sharma et al., 1995). This implies that the smaller the downward water loss, the larger the lateral water loss when standing water is present in the field. In a sequence of rice paddies lying on sloping land, part of the lateral water loss from one paddy becomes an input to the adjacent paddy below. This additional water input may be less at upper toposequence positions on account of relatively deep groundwater and therefore large D (Tsubo et al., 2006). Reducing D at the high landscapes may improve water availability on sandy soils in the sloped lowlands. However, further puddling cannot reduce D on clayey soils, as D is already very small (D<1 mm in the present study). In this case, retention of the standing water depends highly on the seasonal distribution and amount of rainfall and the lateral water movement.

The present study analysed variation in water availability across the rainfed lowlands of Northeast Thailand by quantifying each component of the water balance, and confirmed the following points.

(i) Soils with a high clay content can retain standing water in the field until late in the growing season, and when rainfall is high, sandy soils also keep the standing water until crop maturity.

(ii) The downward water flow (D) is negatively correlated with clay content of the topsoil, and it increases with decrease in groundwater level when there is separate perched water table.

(iii) The net lateral water flow (L) could be negatively correlated with clay content of the topsoil, as the paddy field can gain water by lateral movement in high clay soils and losses much water in sandy soils.

Thus, water availability in the paddy field varies largely from paddy to paddy in Northeast Thailand. The location-to-location variation can be explained by a combination of the paddy soil types and the distribution and amount of rainfall during the growing season, and the paddy landscape. The present study showed the positive effect of the soil clay content on paddy water availability. Accordingly this could explain the high water productivity on clayey soils.

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