Modeling a biophysical environment to better understand the decision-making rules for water use in the rainfed lowland rice ecosystem

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Growing rainfed lowland rice (RLR) is the main activity in northeast Thailand. Unpredictable droughts and coarse-textured soil are the principal constraints usually cited to explain the low yields and economic poverty of this region. Past studies tried to improve the drought tolerance of rice varieties and hydrological functioning at the field level. How water is used at the farm level remains largely unknown. Consequently, it is relevant to understand the interactions between the water-resource and water-use dynamics in the RLR ecosystem. This article proposes to develop a simulation tool based on multi-agent systems to explore adaptations of the rice cropping pattern to rainfall variability. An environment containing the main biophysical entities involved in decision-making rules for water use is modeled and its hydrological functioning is verified. Preliminary simulations are run to illustrate the model capacities. These simulations aim at evaluating farm pond capacity to alleviate early drought at the vegetative stage. Simulations comparing scenarios with and without ponds show that ponds are less efficient at the beginning of the RLR cycle, when rains are still light. Pond efficiency is stable when the period separating two seedbed sowings is longer than 2 months. Below this threshold, it is possible that the ponds are not completely refilled. The next step in the model development will consist of adding autonomous agents to simulate scenarios in which farmer agents may cooperate to use water.

Fischer (1996) projected that total rice production must increase by 25% by 2025 to meet the increasing human population needs. Worldwide, 28% of the total rice-growing area is planted with rainfed lowland rice (RLR). Mackill et al (1996) define the rainfed lowland ecosystem as areas where rice is grown in unirrigated, leveled, and bunded fields that have shallow flooding with rainwater. The northeast Thailand region is mainly a large plateau on sandstone, which is usually characterized by poor soils and erratic rainfall. It covers one-third of the Kingdom area and also corresponds to a third of its total population. This region is the poorest of the country and is still a major rainfed lowland rice-growing area. Farmers practice rice monocropping mostly in the wet season. A common feature across the rainfed production environment, which is clearly distinguished from the irrigated system, is uncertain water supply. Past efforts to alleviate water stress in RLR (varietal improvement, irrigation, soil compaction, etc.) had limited effect. For some years, the construction of farm ponds that began and was subsidized by the King's patronage seemed to be successful in mitigating drought at the farm level (Hungspreug 2001). Although water availability has been improved, farmers do not seem to take this opportunity to intensify their rice production. They still grow traditional types of RLR cultivars, which provide low yield but high grain quality.

New research is needed to identify actual water needs in local farming systems based on the use of traditional RLR cultivars and to determine appropriate improvement pathways as farmers will probably continue to grow this type of RLR. An understanding of existing patterns of water use and water users' needs is required to improve the current situation. This article proposes to develop a simulation tool based on multi-agent systems to explore adaptations of the rice cropping pattern to rainfall variability. To do this, we propose three complementary steps: (1) identifying hydrological dynamics, (2) understanding farmers' decision-making rules regarding water use, and (3) integrating both components into a multi-agent simulation. This model should help in analyzing the system's functioning and evaluating its sensibility to parameters such as the date of seeding and transplanting, which vary according to rainfall variability. Our article presents the different stages of the modeling process, from data collection and field studies to computer simulations of scenario assessment by means of model implementation and verification.

Water resources and rainfed lowland rice in northeast Thailand

More than 80% of the farmed area in northeast Thailand (NET) is used to grow RLR (Office of Agricultural Economics 2001). The cropping cycle usually starts with the beginning of the rainy season, in late April, when fields are still unflooded. Rice is first seeded in nurseries near water sources so that complementary irrigation can be applied in case of drought. Approximately 1 month later, rice seedlings are transplanted in flooded fields after the water table has moved up and the rivers spread out in flooded plains. Paddy fields are usually harvested after rains have stopped and the land has drained. Therefore, this agroecosystem is characterized by a low water control and farmers have to adapt the crop calendar to the rainfall pattern. Their room to maneuver for water management is very limited and they often face unavoidable dry spells.

In northeast Thailand, this situation is made worse by disadvantageous natural conditions. The high rainfall variability causes successions of dry spells even during the rainy season (Fukui 1993). Water stress is aggravated by very coarse-textured soils with low water retention and salinity problems (Trébuil et al 1998). This unfavorable natural environment is usually cited to explain the low rice yields (1.8 t ha^{-1}) and the relative economic poverty of this region (Somrith 1997). Past agronomic research focused on improving rice varieties to increase their tolerance of drought (Singh et al 1996). At the same time, government agencies implemented water development projects to increase irrigated area and the availability of water resources at the farm and community levels. The results are not very satisfactory as most irrigation schemes have been underused and improperly maintained. An important reason is that farmers did not actually participate in all stages of project development (Patamatamkul 2001).

Several models have already been built to represent the biophysical environment of the RLR ecosystem. The RLRice, Rainfed Lowland Rice model (Fukai et al 2000), simulates the growth of many rice varieties according to the amount of water available. The ORYZA model (Bouman et al 2001) is made up of different modules that calculate water deficiency according to soil, climate, and plant physiology. Other models propose spatial representations (Suzuki et al 2001, Kam et al 2001) that take into account hydrological conditions according to field position along the toposequence, or depend on the soil type and climatic conditions at the regional level. All these models have the same aim: to calculate the terms of a water balance to predict a level of water stress and related RLR yield loss. They were helpful in conceiving the structure of our own model. Particularly, they provided representations of the main water transfers to be considered in the RLR ecosystem. Nevertheless, the "water use" component was rarely considered in these past studies. The formalization of interactions between the water-resource and water-use dynamics requires a model allowing the representation of the diversity of water uses and water access, as well as their determining parameters. Several models have been developed to represent such interactions in other regions and toward the world.

As multi-agent systems (MAS) have proved to be particularly adapted to represent such dynamics (Ferber 1999), we present hereunder some of their applications, with a focus on their hydrological structure and functioning. CATCHSCAPE (Becu et al 2001) is a MAS designed to comprehend the interactions of conflicts between upstream and downstream activities in an irrigated rice ecosystem in northern Thailand. At the field level, crop yield is calculated using a two-reservoir water balance model already validated and calibrated in northern Thailand catchments. SHADOC (Barreteau and Bousquet 2000) is a MAS designed to explore the viability of irrigated systems in Senegal. A pump controls the water discharge entering the irrigated network. At the field level, a water balance model calculates the water deficiency from which a yield loss is estimated. Rainwater is absent. Ducrot et al (2003) articulate land and water dynamics with urbanization in a MAS that combines to examine the connections among the hydrological process (water cycle, pollution), land-use changes, and urbanization. The hydrological process is mainly used to monitor the pollution process, which transfers into the catchments (surface runoff and river flow). Although all the research mentioned above used the MAS approach to build hydrological models, it did not strongly emphasize the precision of water balance or water transfer.

The SINUSE model (Feuillette 2003) based on MAS was built to explore groundwater management in the Merguellil watershed of Tunisia. It emphasized simulations of water-table and user interactions with a special focus on economic and social interactions. The main physical criterion that farmers take into account when they use water is water-table depth. To restitute its spatial heterogeneity, the water table is modeled with five tanks having their own hydrodynamic parameters and connected to each other. Although rainfall data series are used in the simulations, the aquifer recharge is calculated using a hydrogeological model disconnected from these series. All these MAS models favored social dynamics in their development. Hydrological processes were extremely simplified as they are comparatively less relevant regarding the research question. The surveys conducted in the RLR ecosystem revealed that farmers' adaptations to rainfall variability closely depend on the water availability in the natural or artificial sources (ponded water in paddy field, soil moisture, river, ponds, water table). The water dynamics of these entities are closely interconnected in step with the hydrological process at the subwatershed scale. Consequently, the representation of water transfers from the rainfall to the subwatershed outfall was considered of paramount importance to initiate the model conceptualization.

Materials and methods

This research was carried out in the Land Reform Area of the Lam Dom Yai watershed in southern Ubon Ratchathani Province. Considering that northeast Thailand is divided into micro-watersheds with similar socioeconomic and biophysical organizations (Khon Kaen University-Ford Cropping Systems Project 1982), the Huay Bua subwatershed was selected for this study as its farming systems and hydrological conditions were found to be representative of the regional diversity in hydrological processes, water access, and water use (Fig. 1). To assess this diversity, 32 semi-structured interviews were conducted with farmers in early March 2003, during the

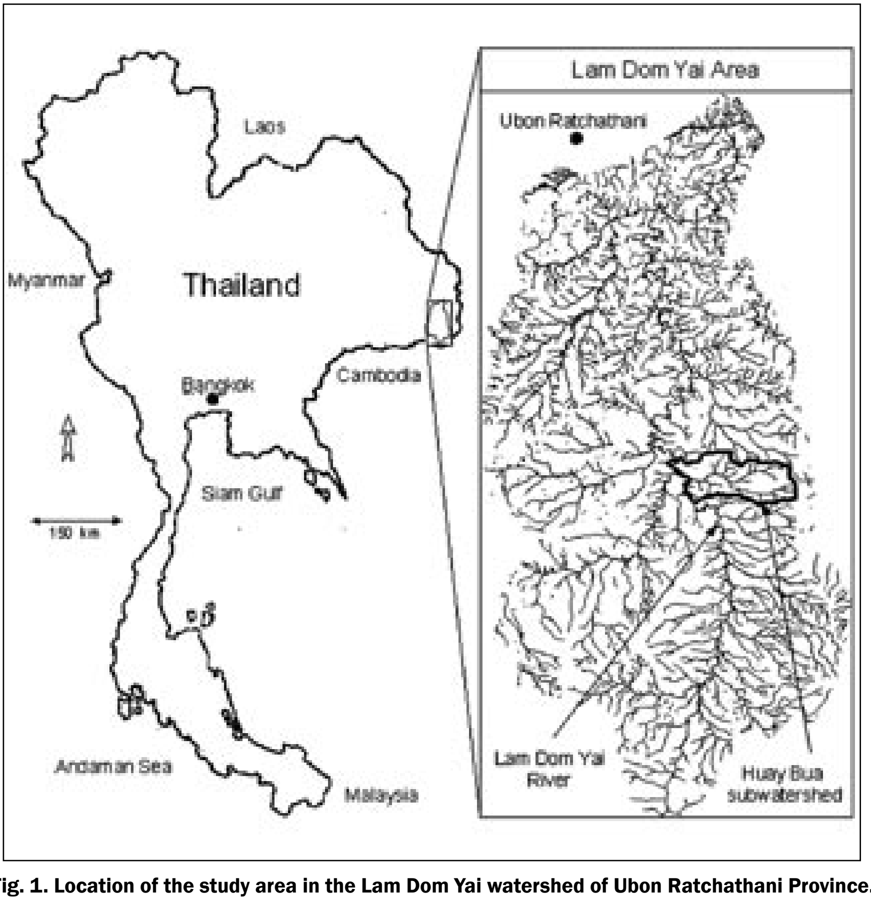

Fig. 1. Location of the study area in the Lam Dom Yai watershed of Ubon Ratchathani Province.

dry season, in seven villages distributed across the study area. These villages were chosen according to their location along the toposequence and the selected sample of villagers aimed at covering the diversity of farm types. In late May, a new series of surveys was conducted to fill some knowledge gaps, particularly to determine the dimensions of farm ponds and their spatial density, useful for the model conceptualization. A frequency analysis of rainfall (data not shown) based on data from several meteorological stations in Ubon Ratchathani Province was carried out to quantify the spatial and temporal variability of rainfall, to assess its possible consequences for water management, and to guide the implementation of the pattern of rainfall distribution in the model. The CORMAS (common-pool resources and multi-agent systems) platform was used to implement the model because its entities could be spatialized and represented on a metered grid, and because of the possibility it allows to model farmers' decision-making rules regarding water use.

Conceptualization of the model

Three main water uses were identified: the phase of land preparation for rice production (April-May), the supplementary irrigation of rice fields during the early vegetative phase (June-July), and the irrigation of vegetable crops during the first half of the dry season (December-February). The water volumes corresponding to domestic uses were considered as negligible compared with agricultural uses. The major factors involved in farmers' decision-making processes concerning water use were as follows: rice varieties (early or late-maturing types, for self-consumption or for sale, more or less tolerant of drought); the position of fields and ponds along the toposequence, which determines the accessibility to water resources and the amount available; soil moisture; and customs and religious events such as the Royal plowing ceremony and the Thai New Year that may influence the cropping calendar. All these factors determine the date, frequency, and location of water uses. The two main RLR varieties grown in this region are KDML105 and RD6; both are photosensitive varieties. KDML105, a nonglutinous variety, is usually seeded in nurseries in late April near a source of water to compensate for the lack of rain because rain is still light at this time. As this variety is more tolerant of water stress, it is usually transplanted in the upper paddies (Fig. 2). RD6, a glutinous and late-maturing variety, is mainly grown for family consumption. This variety is usually seeded in June, when labor is available after KDML105 transplanting, and is preferably transplanted in lower paddies where water is more abundant. In this way, farmers prioritize their family food security by growing RD6 in a safer area regarding water source as RD6 is harvested after the drainage of these lowlands. Figure 3 illustrates the synchronism between the rice cropping pattern and seasonal variability. Such an understanding of the spatial and temporal distribution of RLR helps when selecting the biophysical factors involved in decision-making that should be included in the model. Some of them vary (1) in space: accessibility to water resources, soil hydraulic properties, the position of fields, and sources of water along the toposequence; (2) in time: rainfall, the quantity of water available, and soil moisture; and (3) in both time and space: rice varieties. A map displaying elevation, soil series, and the hydrographic network was used to determine the slope, the pattern of soil distribution, and the streams to be represented in the model.

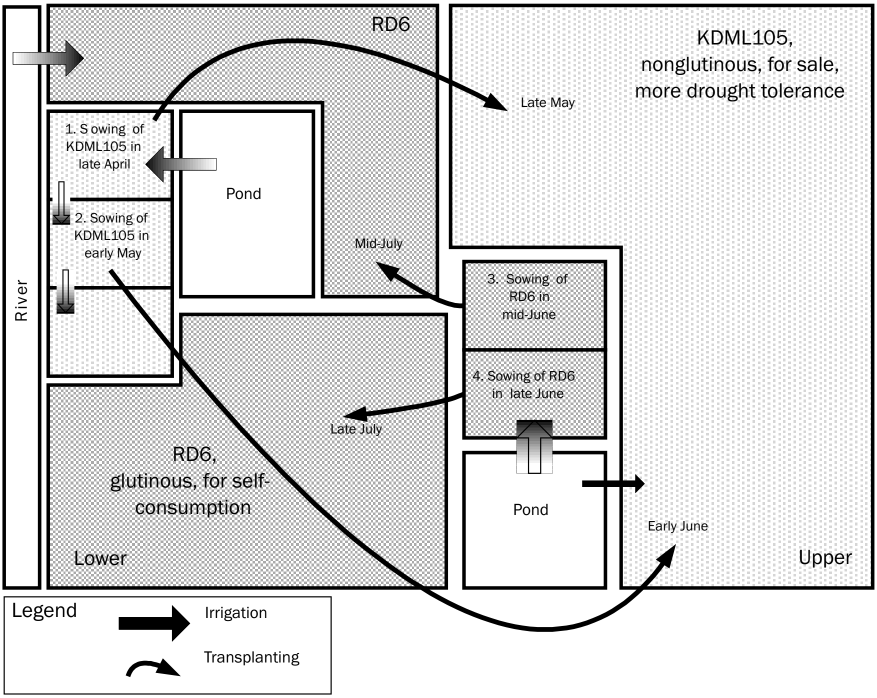

Fig. 2. Main water uses and rice cropping pattern at the farm level in the Lam Dom Yai area of Ubon Ratchathani Province.

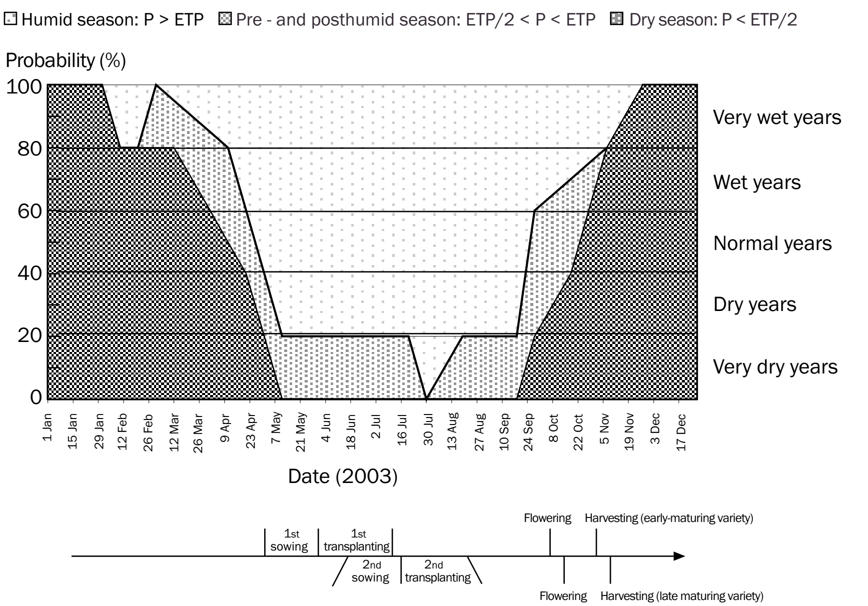

Fig. 3. Seasonal variability (adapted from Franquin 1985) and synchronism with the crop calendar.

Suitable time steps and spatial units had to be defined. The time steps should be compatible with the length of the simulated periods and with the time base of input data, such as rainfall and evapotranspiration. Decisions on water use usually consist of choosing a date and a frequency of the use. This date can vary from one day to another according to daily rainfall distribution or habits. Consequently, a single-day time step was chosen. Because farmers' decision-making criteria linked to water uses may vary among fields according to their location, soil characteristics, and distance from a source of water, the RLR field was selected as the key spatial unit in the model. The size of the area represented in the model was defined according to the total number of fields to be represented. According to field observations and measurements, the average field size was 800 m^2 and varied from 100 to 1,600 m^2. As the surface of the entire Huay Bua watershed is 11,250 ha, corresponding to some 140,625 fields, it was not possible to represent all these fields in the model because such a large number of fields will unnecessarily slow down the simulations. The area represented in the model corresponds to 50 ha made up of 625 fields. We believe that the real diversity of the fields' spatial organization is retained in this scale change.

As several decisions concerning water use depend on distances between fields and reservoirs, attention had to be paid to this scale transfer. Following a second series of field surveys, average dimensions and standard deviation were calculated to determine the size and the spatial density of entities to be represented in the model to create a realistic environment. As the modeled area represents the Huay Bua River, the average distance between the fields and the river is artificially minimized. In some cases, this distortion may affect the decision-making rules linked to distance and it will have to be taken into account during model simulations. Another scale-transfer problem concerns the water-table level, which is normally correlated to the total volume of rainwater received in the watershed. In the model, the surface receiving rain is smaller than the whole watershed. To take into account the groundwater coming from the whole watershed and to determine the level of the water table, a correction coefficient had to be used during the model calibration to artificially increase the amount of rainwater percolating into the water table.

Structure of the model

The hydrological process represented in the model should involve all water entities (ponded water in paddy field, soil moisture, water table, ponds and rivers) that may interact with water uses and whose water volume may vary according to the rainfall pattern.

The model structure relies on hydrological entities. These entities are divided into two categories: the ones supplying water (such as the pond, the river, the water table) and the entities consuming water (such as the RLR fields). All these entities are organized into two layers: a first layer is made up of the water table and river entities (Fig. 4). To represent the natural slope of the watershed, these entities are terraced at three elevations (130, 131, and 132 m) as shown in Figure 4. The main horizontal water transfers (except for surface runoff) occur at this layer level: the Huay Bua River is made up of three tanks, and each tank has a threshold. If the water level exceeds this threshold, the excess water flows into the downstream tank. Each of the three river tanks receives water from the two neighboring water-table tanks (Fig. 5). The

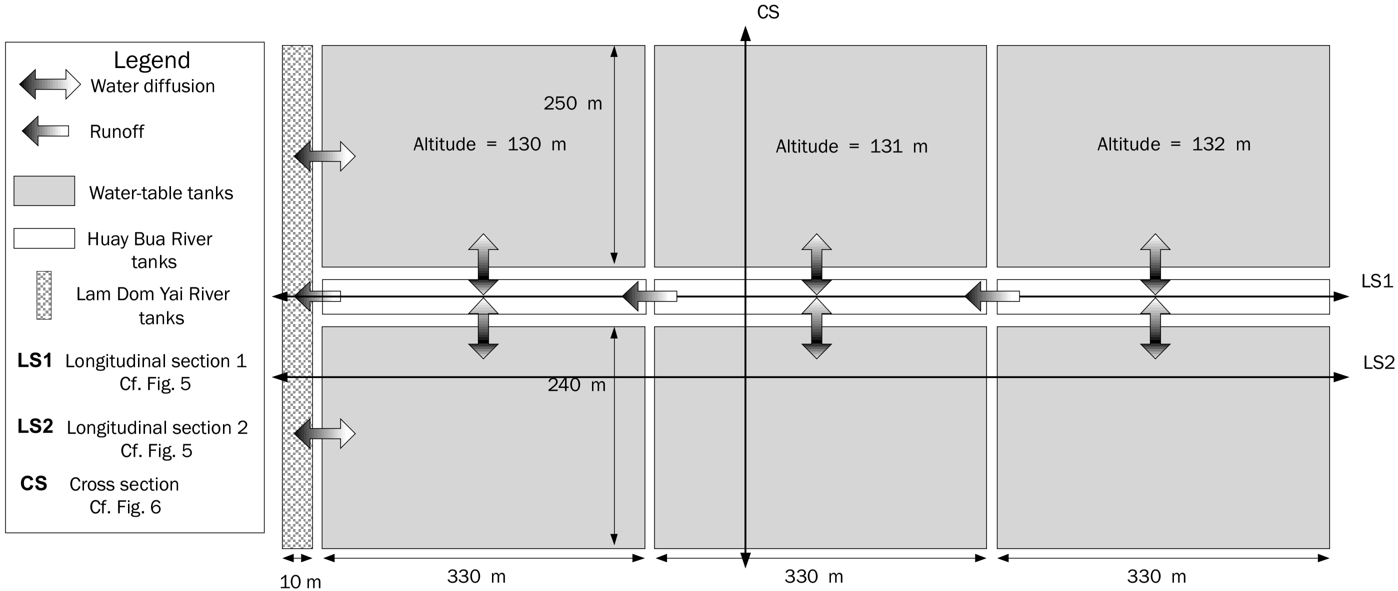

Fig. 4. First layer of the model spatial entities representing the water table and rivers.

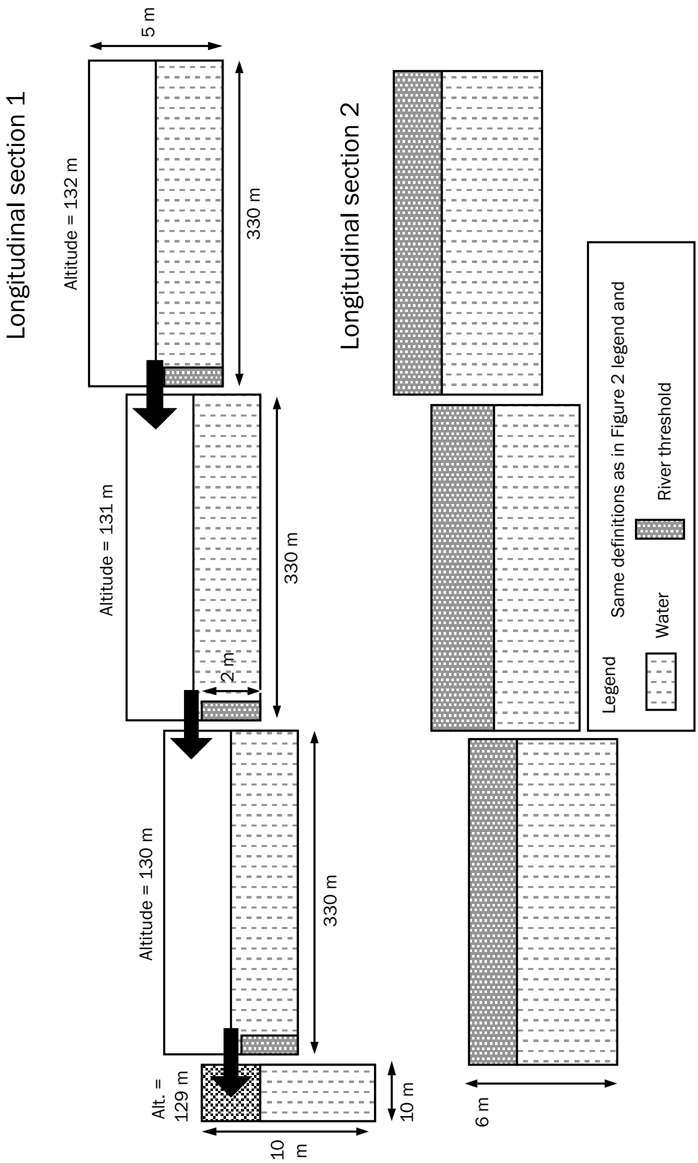

Fig. 5. The three-level terraced entities of the first layer in the model.

lack of precise data concerning soil hydrodynamic parameters forced us to simplify the representation of these transfers: in this way, water transfers between water-table tanks were neglected. This first layer is overlaid by a second layer made up of the RLR fields and the pond entities (Fig. 6). Each field is made up of a root-zone tank and a ponded-water tank. Ponds are made up of a single tank. The vertical water transfers occur at this layer level: rain falls into the ponds, the ponded-water tank, and the river tanks. The rain collected in the ponded-water tanks seeps into the root-zone tanks and water in the root-zone tanks percolates into the water-table tanks. These model entities are represented on the CORMAS grid by an aggregate of cells.

The spatial soil variability in northeast Thailand has been identified as an important factor that may interact with farmers' decision-making regarding cropping patterns and water uses (Oberthür and Kam 2000). To represent this variability, a map of the soil series was used. Six soil series were identified in the Huay Bua watershed and one of these series is attributed to each cell of the grid (Fig. 7). For each soil series, three kinds of hydraulic parameters were estimated or calculated using textural class equations and experimental measurements (Akatanakul 1985): the total porosity was used to determine the soil moisture of the rooting zone using the volume of water in the tank. The soil moisture at field capacity was used to calculate the rates of percolation and evapotranspiration on a cultivated soil. Percolation stops when soil moisture of the root zone is below the field capacity. Evapotranspiration is maximal when the root-zone soil moisture is superior to the field capacity. Saturated hydraulic

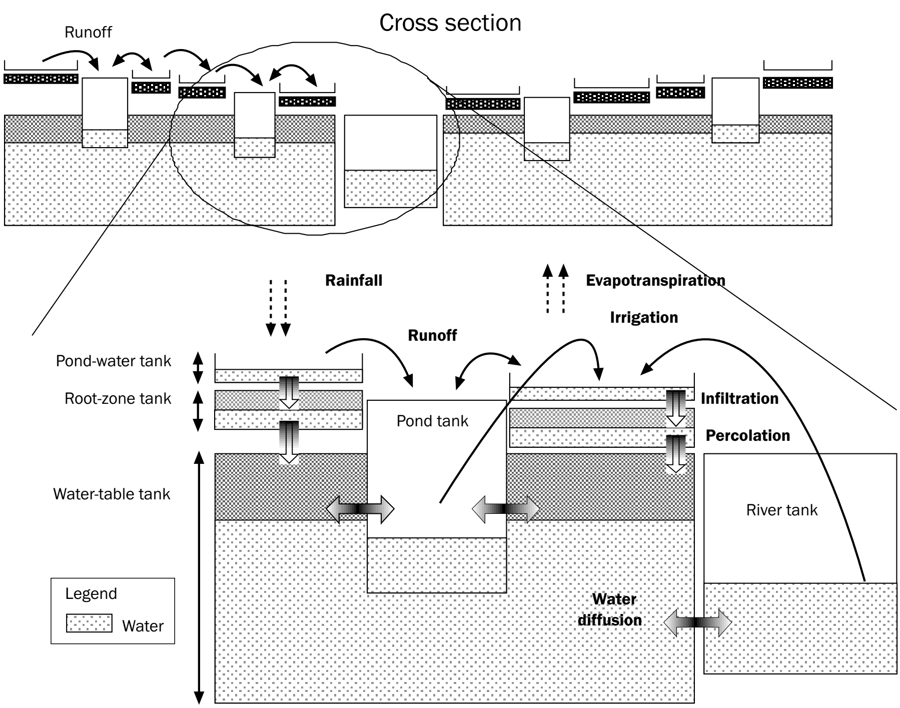

Fig. 6. Structure and hydraulic functioning of the multi-agent model.

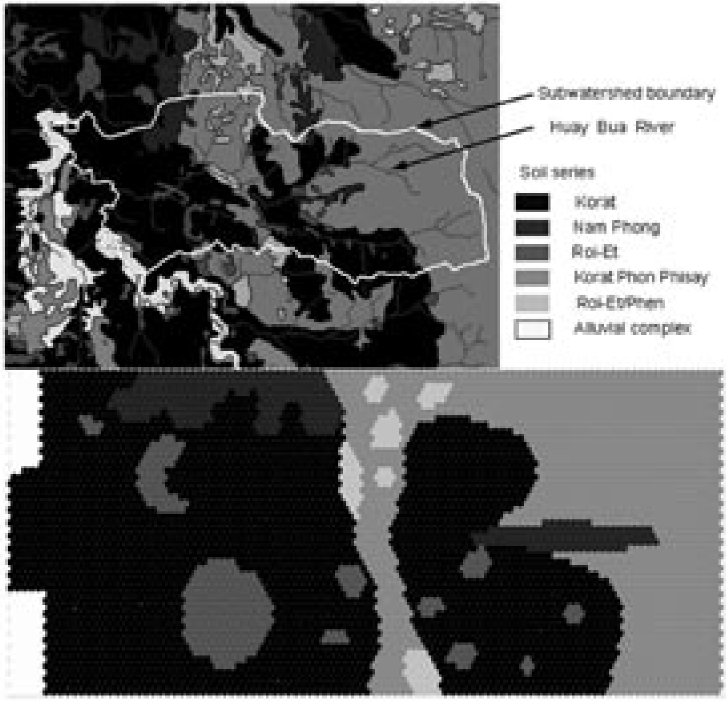

Fig. 7. Distribution of the soil series (A) on the soil map and (B) on their representation on the CORMAS grid.

conductivity was used to determine the maximum transfer for infiltration, percolation, and diffusion (Table 1) (Lacombe 2003).

Several decisions concerning the use of pond water depend on the volume available and the distance from the field to the reservoir. The diversity of possible situations regarding the location and size of fields and ponds is realistically represented in the model. For each aggregate, the number of cells is determined to represent the actual relative variability in size of each entity. The grid representing an area of 50 ha and 625 fields is made up of 5,000 cells and each cell is equivalent to 100 m^2. Each aggregate corresponding to a field consists of several cells varying from 1 to 16. According to our field surveys, there is an average of three ponds for 10 ha of paddy, and so 15 ponds are shown on the grid. Each pond is made up of 2 to 8 cells, as shown in Figure 8. The Huay Bua River is made up of a linear aggregate crossing the grid from east to west, whereas the Lam Dom Yai River is represented by the same kind of aggregate following the west side of the grid. The Lam Dom Yai River is wider (2 cells) than the Huay Bua River (1 cell) in accordance with the field observations. Each pond tank is partially submerged in the water-table tank as displayed in Figure 6 and this structure determines the water level in the ponds after a hydrostatic equilibrium has been reached. This water level may vary between ponds according to their respective locations along the virtual toposequence, as is also the case in reality.

Table 1. Model parameter values for different soils.

Tanks of each soil series	Soil total porosity ($cm^3\ cm^{-3}$)	Soil moisture at field capacity ($cm^3\ cm^{-3}$)	Saturated hydraulic conductivity ($mm\ d^{-1}$)
Korat			
Root-zone tank	0.36	0.19	5,387
Water-table tank	0.40		1,379
Roi-Et			
Root-zone tank	0.39	0.27	1,891
Water-table tank	0.39		1,830
Korat/Phon Phisai association			
Root-zone tank	0.36	0.18	5,233
Water-table tank	0.43		509
Roi-Et/Phen			
Root-zone tank	0.37	0.24	1,762
Water-table tank	0.37		1,714
Nam Phong			
Root-zone tank	0.34	0.21	1,250
Water-table tank	0.38		1,250
Alluvial complex			
Root-zone tank	0.36	0.22	3,104
Water-table tank	0.39		1,336

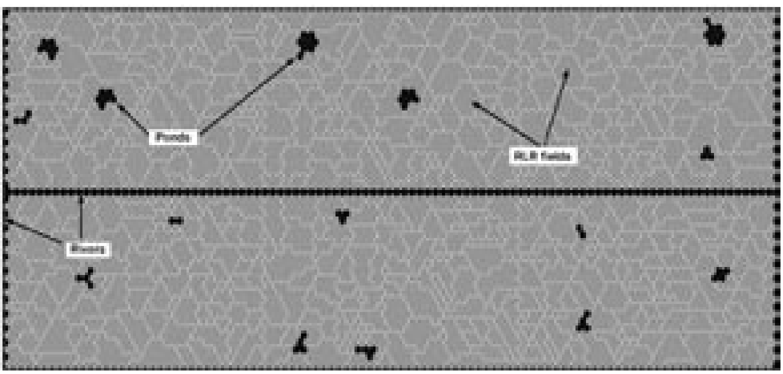

Fig. 8. The model spatial entities as represented on the CORMAS grid (the water-table entities are not represented).

Verification and calibration of the model

Model verification aims to control that each of the model entities is performing its functions properly. By choosing simple initial conditions, it is possible to observe the variation in water level and water transfer, inside and between tanks, and then to compare the model evolution with predictable behaviors. The verification is repeated for each entity and each associated parameter. As an example, one simple model consists of verifying the functioning of water transfer between a ponded-water tank, initially full of water, and its root-zone tank, initially set as being dry. Figure

9 displays the initial drop in the ponded-water level. This decrease is first rapid and constant and then slows down when the root-zone tank reaches saturation. When the root-zone humidity exceeds the field capacity, the percolation function is activated (as soon as time-step 3) and starts draining the root zone. As soil moisture decreases, the infiltration function is slowly reactivated. At time step 9, infiltration increases again because of the root-zone soil moisture drop. When there is no more ponded water, the root-zone tank continues to drain out until it reaches field capacity. Another scenario was run to verify the evapotranspiration function in the model. The ponded-water and root-zone tanks were initially set as full and the percolation and rainfall transfers were inactivated. The two tanks had losses only by evapotranspiration (Fig. 10). Initially, the evapotranspiration function affected only the ponded-water tank for nearly 40 days. Even if RLR roots absorb water from the root-zone tank, evapotranspiration is

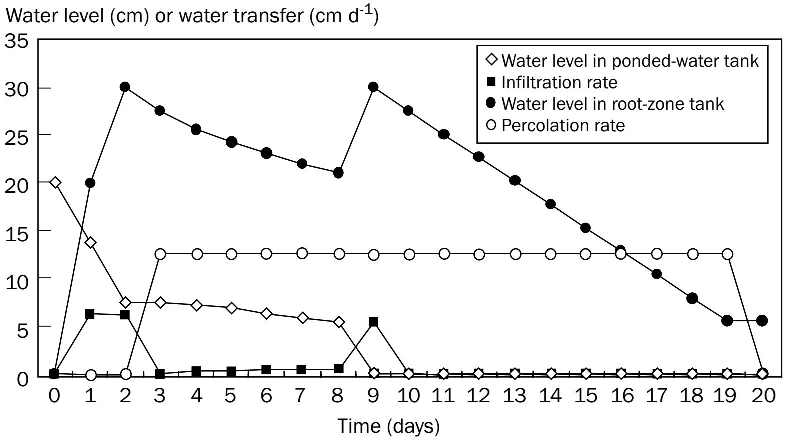

Fig. 9. Verification of infiltration and percolation functions in a simulated field.

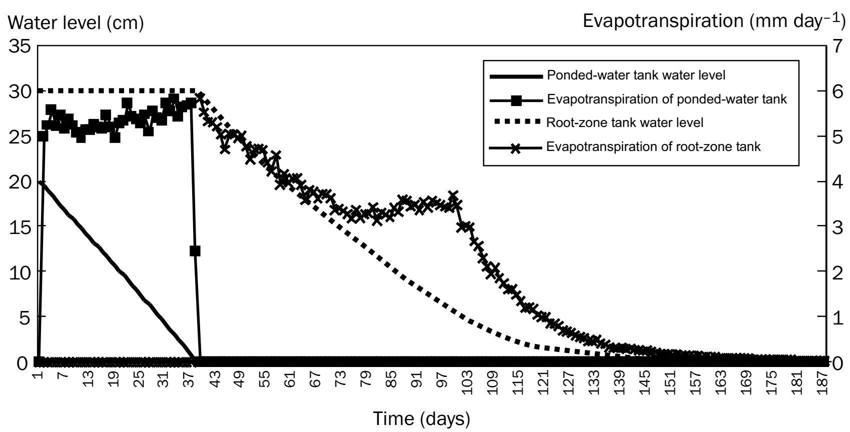

Fig. 10. Verification of the evapotranspiration function at the simulated field level.

set to zero since the climatic demand is mainly satisfied by the physical evaporation from the ponded-water tank. As soon as ponded water disappears, evapotranspiration from the root-zone tank starts. It is maximal at the beginning and then it decreases because of the decline in soil moisture content. Thresholds appear at time-steps 75 and 100. The first threshold is due to the roots' absorption moderating the decline in evapotranspiration, even if the soil moisture continues to decrease. The second threshold appears as the soil moisture content drops below field capacity: beyond this threshold, the roots do not affect the evapotranspiration rate anymore. These two examples illustrate the methods that were used to verify the functioning of each tank and its associated water transfer functions.

After its verification, the model was calibrated. The model parameters such as water levels or water transfers should display realistic variations in time and space. The water table is the model entity for which the water-level variations are well known. Piezometric measurements made by Torii and Minami (1985) helped in calibrating this parameter by defining coefficients to adjust the variations in the water table calculated by the model. By modifying the percolation rate (water transfer from root zone to water table) and the diffusion rate (water transfer from the water table to the river), it was possible to correct the water-table level variations to make the water-table level more coherent with the available empirical data. According to surveys, ponded water appears in RLR fields at the beginning of August and usually disappears in late October when rains stop. Infiltration and percolation transfers had to be calibrated so that the water level in the ponded-water tanks would follow these yearly variations with some spatial variability according to the field position along the toposequence and the soil type (different permeability). Figure 11 shows the variations in water levels in the six water-table tanks of the model along the year. An initialization artifact consists of setting the water level at the same value for the six tanks at the beginning of each year. We assume that there is no hydrological linkage between years.

Exploring scenarios with simulations

Although we have chosen the multi-agent systems approach to create our model, it doesn't include any autonomous agent able to make decisions yet. Consequently, at

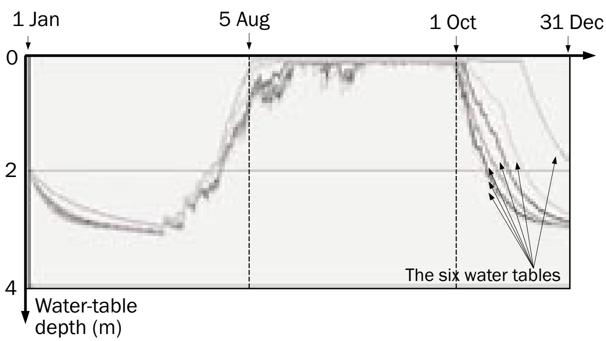

Fig. 11. Calibration of the water levels in the six water-table tanks of the model.

the present stage of development of this model, the decision-making rules we wish to simulate need to be decided at the initialization of the model and they cannot evolve during the simulation. For this, two functions were created. The "irrigation" function takes water from the ponds or the rivers and transfers it to the RLR fields or nurseries when their root-zone moisture content has dropped below a value corresponding to the water-stress threshold. As precise information on RLR wilting point in the Huay Bua watershed is not available, this value is arbitrarily set to the moisture level at field capacity. At each time-step, a second "evaluate water stress" function calculates the proportion of water-stressed fields that couldn't be watered because of insufficient water volume in the ponds or in the rivers or because they are located too far from the water sources. This function is based on a hydrological point of view and should be readjusted through validations.

An important question concerns the assessment of the efficiency of these ponds to decrease the proportion of water-stressed fields during dry spells. This efficiency can be estimated by comparing the proportion of water-stressed fields after running simulations with and without ponds. Scenarios were defined to analyze the sensitivity of pond efficiency to parameters that farmers can manipulate according to their objectives related to rice sales or family consumption and cost and availability of the labor force. Such parameters could be the dates for early and late seeding of their seedbeds or the number of days between these two sowing periods. It is possible to observe the variations in pond efficiency and their correlations with these sowing dates (Fig. 12A). Pond efficiency increases with the proportion of late-seeded nurseries because the ponds have a limited capacity to store rainwater at the beginning of the rainy season, which is characterized by light rain showers, and they are more efficient later in the year. Figure 12B shows the effects of the duration of the period between the two seeding dates on pond efficiency. For a period longer than 2 months, pond efficiency is maximum and stable. Below this threshold, the efficiency is limited by a too short period between sowings.

Discussion

These simulations illustrate the dilemma that farmers have to face: early sowing of RLR nurseries may be important for farmers who wish to sell their rice crop as early transplanting maximizes the length of the vegetative phase during which the plant accumulates dry matter. At the same time, early sowing increases the risk of drought, which occurs frequently in the early part of the wet season. Although these results should be further discussed with farmers to validate the model, these first simulations aim at showing the possible uses of the simulator. This model contains the main biophysical entities involved in the decision-making rules regarding water use. It offers an environment predisposed to receive autonomous farmer-agents, which could help us to better understand the interactions between water supply and demand. Introducing such farmer-agents would allow us to model irrigation processes depending on individual decisions based on the perceptions of the water-resources dynamics rather than using irrigation functions (used in this model) whose criteria are fixed by the modeler.

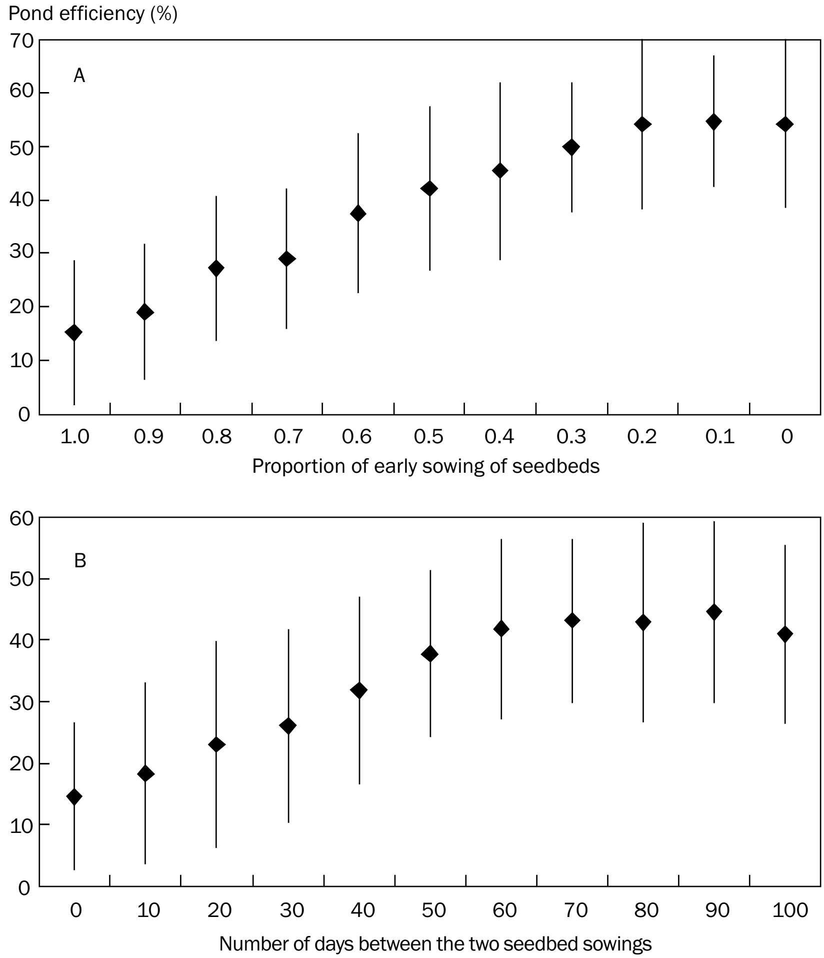

Fig. 12. Sensitivity analysis of pond efficiency according to variations in the proportion of early sowing of seedbeds (A) and the duration between the two nursery seeding periods (B).

Conclusions

The initial simulation results depend on the parameters that were chosen during the model conceptualization and their respective values implemented in the model and then corrected during the verification and calibration steps based on the "expert" knowledge of the modeler. These simulation results should be interpreted with care and must be further validated by transmitting them to the farmers to assess their degree of correspondence with actual circumstances based on the farmers' empirical experience.

An increasing number of wells used for the irrigation of rice and vegetables was observed during the field surveys. This simulator could help to explore scenarios of change in the use of water tables to evaluate the possible consequences of this emerging pattern of increased well irrigation. Compared to the ponds, the water table may be a more suitable source of water for irrigation, particularly at the beginning of the RLR cycle when rains are still light and the need for water is already important. The next step in the model implementation could also consist of adding autonomous agents making decisions regarding water use. These developments of the model would allow the simulation of new scenarios in which farmer-agents could cooperate. One relevant topic to be explored with them would be the possibility of exploiting common water resources such as the several large collective ponds that are clearly underexploited now.

References

Akatanukul S. 1985. Hydraulic properties of major northeast soils. In: Pairintra C, Wallapapan K, Parr JF. Whitman CE, editors. The first KKU-USAID International Seminar on Soil, Water, and Crop Management Systems for Rainfed Agriculture in Northeast Thailand, held at Khon Kaen University, 25 February-1 March 1985. Bangkok (Thailand): Kasetsart University. p 189-200.

Barreteau O, Bousquet F. 2000. SHADOC: a multi-agent model to tackle viability of irrigated systems. Ann. Operations Res. 94:139-162.

Becu N, Perez P, Walker A, Barreteau O. 2001. CatchScape: an integrated multi-agent model for simulating water management at catchment scale: a northern Thailand case study. In: MODSIM 2001 International Congress on Modelling and Simulation, Canberra, Australia, 10-13 December. 6 p.

Bouman BAM, Kropff MJ, Tuong TP, Wopereis MCS, ten Berge HFM, van Laar HH. 2001. ORYZA 2000: modeling lowland rice. Manila (Philippines): International Rice Research Institute. 235 p.

Ducrot R, Le Page C, Bommel P, Kuper M. 2003. Articulating land and water dynamics with urbanization: an attempt to model natural resources management at the urban edge. Computers Environ. Urban Syst. 28:85-106.

Ferber J. 1999. Multi-agent systems: an introduction to distributed artificial intelligence. New York (USA): Addison-Wesley Longman Inc.

Feuillette S, Bousquet F, Le Goulven P. 2003. Sinuse: a multi-agent model to negotiate water demand management on a free-access water table. Environ. Mod. Software 18:413-427.

Fischer KS. 1996. Research approaches for variable rainfed systems: thinking globally, acting locally. In: Cooper M, Hammer GL, editors. Plant adaptation and crop improvement. Wallingford (UK): CAB International in association with IRRI and ICRISAT. p 25-35.

Franquin P. 1985. La climatologie fréquentielle en agriculture tropicale. Tech. Dével. 5:6-15.

Fukai S, Basnayake J, Cooper M. 2000. Modeling water availability, crop growth, and yield of rainfed lowland rice genotypes in northeast Thailand. In: Tuong TP, Kam SP, Wade LJ, Pandey S, Bouman BAM, Hardy B, editors. Characterizing and understanding rainfed environments. Manila (Philippines): International Rice Research Institute. p 111-130.

Fukui H. 1993. Food and population in a northeast Thai village. Monograph of the Center of Southeast Asian Studies, Kyoto University. No. 19. Honolulu, Haw. (USA): University of Hawaii Press. 421 p.

Hungspreug S. 2001. Water management in the Korat Basin, northeast Thailand: policy, institutional, and management issues from the farm/village to the region. In: Kam SP, Hoanh CT, Trébuil G, Hardy B, editors. Natural resource management issues in the Korat Basin of northeast Thailand: an overview. Manila (Philippines): International Rice Research Institute. p 119-124.

Kam SP, Tuong TP, Bouman BAM, Fajardo S, Reyes JP. 2001. Water-balance modeling to study regional drought risk and crop management strategies. In: Program report for 2000: rainfed lowland rice ecosystem. Los Baños (Philippines): International Rice Research Institute. p 26-29.

Khon Kaen University-Food Cropping Systems Project. 1982. An agroecosystem analysis of Northeast Thailand. Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand.

Lacombe G. 2003. Compréhension des stratégies d'adaptation à la variabilité des pluies en riziculture inondée par la modélisation Cas du bassin versant de la Lam Dom Yaï, région Nord-est de la Thaïlande. Mémoire de DEA "Sciences de l'Eau dans l'Environnement Continental." Ecole Nationale du Génie Rural, des Eaux et des Forêts-Université Montpellier II, France.

Mackill DJ, Coffman WR, Garrity DP. 1996. Rainfed lowland rice improvement. Manila (Philippines): International Rice Research Institute. 242 p.

Oberthür T, Kam SP. 2000. Perceptions, understanding and mapping of soil variability in the rainfed lowlands of northeast Thailand. In: Tuong TP, Kam SP, Wade L, Pandey S, Bouman BAM, Hardy B, editors. Characterizing and understanding rainfed environments. Manila (Philippines): International Rice Research Institute. p 75-95.

Office of Agricultural Economics. 2001. Agricultural statistics of Thailand, crop year 2000/2001. Center for Agricultural Information, Agricultural Statistics No. 9/2001, Bangkok, Thailand.

Patamatamkul S. 2001. Development and management of water resources in the Korat Basin of northeast Thailand. In: Kam SP, Hoanh CT, Trébuil G, Hardy B, editors. Natural resource management issues in the Korat Basin of northeast Thailand: an overview. Proceedings of the Planning Workshop on Ecoregional Approaches to Natural Resource Management in the Korat Basin, Northeast Thailand: Toward Further Research Collaboration, held on 26-29 October 1999, Khon Kaen, Thailand. Los Baños (Philippines): International Rice Research Institute. p 115-118.

Singh VP, Singh RK, Singh BB, Zeigler RS. 1996. Physiology of stress tolerance in rice. In: Proceedings of the International Conference on Stress Physiology of Rice, 28 Feb-5 March 1994, Lucknow, Uttar Pradesh, India. 239 p.

Somrith B. 1997. Cultivar improvement for rainfed lowland rice in Thailand. In: Fukai S, Cooper M, Salisbury J, editors. Breeding strategies for rainfed lowland rice in drought-prone environments. Proceedings of an International Workshop held at Ubon Ratchathani, Thailand, 5-8 November 1996. ACIAR Proceedings 77. p 36-42.

Suzuki K, Goto A, Mizutani M, Sriboonlue V. 2001. Modeling of hydrologic processes in rainfed paddy fields in northeast Thailand. International Commission on Irrigation and Drainage 1st Asian Regional Conference, Seoul, Korea.

Torii K, Minami I. 1985. Application of a mini-pond system to rural development in northeast Thailand, on the model of the Tameike system in Toban District, Japan. Irrig. Eng. Rural Plan. No. 8.

Trébuil G, Harnpichitvitaya D, Tuong TP, Pantuwan G, Wade LJ, Wonprasaid S. 1998. Improved water conservation and nutrient-use efficiency via subsoil compaction and mineral fertilization. In: Ladha JK, Wade LJ, Dobermann A, Reichardt W, Kirk GJD, Piggin C, editors. Rainfed lowland rice: advances in nutrient management research. Los Baños (Philippines): International Rice Research Institute. p 245-256.

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