A Multi-Agent Model to Help Managing Rainfall Variability in the Rainfed Lowland Rice Ecosystem of Northeast Thailand

Lacombe G., US DIVHA/UMR Hydrosciences Montpellier, IRD, Université Montpellier II, France, guillaume.lacombe@msem.univ-montp2.fr, guillaume.lacombe@ird.fr

Bousquet F., Green research unit, Tera department Cirad, Montpellier, France. Seconded to the Social Sciences Division, The International Rice Research Institute, Los Baños, Laguna, Philippines.

Naivinit W., Faculty of Agriculture, Ubon Ratchathani University, Thailand.

and G. Trébuil, Green research unit, Tera department Cirad, Montpellier, France. Seconded to the Social Sciences Division, The International Rice Research Institute, Los Baños, Laguna, Philippines.

Abstract

Rainfed lowland rice (RLR) production is the main activity in northeast Thailand. Unpredictable droughts and coarse-textured soil are the main 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 dynamic interactions between water availability and water-use in the RLR ecosystem. This article describes the development of an agent-based simulation tool based on multi-agent systems to explore adaptations of RLR cropping systems to rainfall variability. An environment representing the main biophysical entities involved in decision-making regarding water use is modeled and its hydrological functioning is verified. Preliminary simulations are presented to illustrate the model capacities. These preliminary simulations aim at evaluating the efficiency of numerous on-farm reservoirs 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 duration of the period separating the two peaks of RLR nursery sowings is more than 2 months. Below this threshold, ponds could not be completely refilled. The next step in the model development will consist in adding autonomous agents to simulate scenarios in which farmer agents cooperate to use water and learn collectively about its dynamics.

Introduction

The northeastern region of Thailand is a large plateau on sandstone, which is usually characterized by poor soils and erratic rainfall. It covers one-third of the Kingdom and is home for a third of its total population. This region is the poorest of the country and a key RLR growing area. Farmers practice RLR monocropping mostly in the wet season. A common feature across the rainfed production environment is uncertainty of water supply. Past efforts to alleviate water stress in RLR (crop improvement, irrigation, soil compaction, etc.) had limited effects. For the last 15 years, the construction of small on-farm reservoirs seems to be more successful in mitigating drought at the farm level and promoting diversification of agricultural production (Hungspreug 2001). Although water availability has been improved, farmers do not seem to fully use this opportunity to intensify agricultural production.

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 in the near future. An understanding of existing patterns of water use and water users' needs is required to improve the current situation. This article describes the development of an agent-based simulation tool relying on multi-agent systems (MAS) to explore adaptations of RLR cropping systems to rainfall variability. To do this, three complementary steps were followed: (1) identification of hydrological dynamics at the catchment level, (2) understanding farmers' decision-making rules regarding water use in RLR, and (3) integrating both components into a multi-agent model to be used for simulating various future scenarios with stakeholders. Later on, this model will be used to promote collective learning about water management across boundaries. The article presents the successive stages of the modeling process, field studies, up to preliminary computer simulations to assess scenarios with farmers.

Water resources and RLR in northeast Thailand

More than 80% of the farmed area in northeast Thailand (NET) is used to grow RLR (OAE 2001). The cropping cycle starts with the beginning of the rainy season, in late April, when fields are still not flooded. Rice is first seeded in nurseries near water sources so that complementary irrigation can be applied during dry spells. Approximately one 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 unpredictable rainfall distributions. Their room for maneuver for water management is very limited.

This situation is made worse by disadvantageous natural conditions. The high rainfall variability causes successions of dry spells even during the rainy season. Water stress is aggravated by very coarse-textured soils with low water retention. This unfavorable natural environment is usually cited to explain the low paddy rice yields (ranging usually from 1.6 to 2.0 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 also 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 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. 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. Multi-agent systems (MAS) have proved to be particularly adapted to represent such dynamics in agroecosystems (Ferber 1999), we present hereunder some of their applications, with a focus on modeling hydrological structure and functioning. CATCHSCAPE (Becu et al 2001) is a MAS model to comprehend the conflicting interactions between upstream and downstream activities in an irrigated rice ecosystem of northern Thailand. At the field level, crop yield is calculated using a two reservoirs water balance model already validated and calibrated for northern Thailand catchments. SHADOC (Barreteau and Bousquet 2000) is a MAS designed to explore the viability of irrigated systems in Senegal. At the field level, a water balance model calculates the water deficiency from which a yield loss is estimated. Ducrot et al (2003) articulate land and water dynamics with urbanization in a MAS to examine the connections among the hydrological process, land-use changes, and urbanization. The SINUSE model developed by Feuillette (2002) is based on a MAS to explore groundwater management in Tunisia. It is used to simulate interactions between water-table movements and water users with a special focus on economic and social interactions. The development of all these MAS models included the analysis of social dynamics. Hydrological processes were extremely simplified as they were comparatively less important regarding the research question to be examined. Surveys conducted in the RLR ecosystem revealed that farmers' adaptations to rainfall variability closely depend on access to water from various sources (ponded water in paddy fields, soil moisture, rivers, ponds, water table). The dynamics of these entities are closely interconnected at the sub-watershed scale. Consequently, in the case of collective water use in RLR catchments, the representation of water transfers from rainfall to sub-watershed outfall was considered of paramount importance in the model conceptualization.

Materials and methods

This research was carried out in 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 sub-watershed was selected for this study as it is representative of the regional diversity in hydrological processes, water access and water use. 32 semi-structured interviews were conducted with farmers in early March 2003, during the 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 and water access. In late May, a new field survey was conducted to fill some knowledge gaps (spatial density and dimensions of farm ponds), 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: land preparation (April-May), supplementary irrigations of rice fields during the early vegetative phase (June-July), and the irrigation of vegetable crops in the first half of the dry season (December-February).

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 to drought); the position of fields and ponds along the toposequence, which determines the accessibility to water resources; soil moisture; customs and religious events 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 KDML 105 and RD 6; both are photosensitive varieties. KDML 105, a non-glutinous variety, is more tolerant to water stress, it is usually transplanted in the upper paddies (Fig. 1). RD 6, a glutinous and also late-maturing variety mainly grown for family consumption is usually seeded in June, and is preferably transplanted in lower paddies. 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.

Suitable time steps and spatial units had to be defined. The time steps should be compatible with the water uses variability. Decisions on water use usually consist of choosing a date and a frequency of the use. This date can vary 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. As the surface of the entire Huay Bua watershed is 11,250 ha, corresponding to some 140,625 fields, it was not convenient to represent all these fields in the model. The area represented in the model corresponds to 50 ha made up of 625 fields but the diversity of the fields' spatial organization was retained.

As several decisions concerning water use depend on distances between fields and reservoirs, attention had to be paid to this scale transfer. Average dimensions and standard deviation were calculated to determine the size and the spatial density of entities to be represented to create a realistic environment. The average distance between the fields and the river is artificially minimized and, in some cases where such distortion may affect the decisions linked to distance, this will have to be taken into account in the 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 Huay Bua catchment. A correction coefficient was 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 fields, soil moisture, water table, ponds and rivers) that may interact with water uses and receive rain water. The model structure relies on hydrological entities: the ones supplying water (ponds, rivers, water-tables) and the entities consuming water (RLR fields). These entities are organized into two layers: a first layer is made up of the water table and river entities (Fig. 2). The main horizontal water transfers (excepted for surface runoff) occur at this layer level: Huay Bua River flow and water-tables drain into the river (Fig. 3). Because of data scarcity, 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. 4). 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 then percolates into the water-table tanks. These model entities are represented on the CORMAS grid by cells aggregates (Fig. 5).

The 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 according to a simplified distribution of the soil types. For each soil series, three 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. 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 conductivity was used to determine the maximum transfer for infiltration, percolation, and diffusion (data not shown).

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 (Fig. 5). Each pond tank is partially submerged in the water-table tank as displayed in Figure 4 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.

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. For example, one simple exercise consisted in verifying the functioning of water transfer between a ponded-water tank, initially full of water, and its root-zone tank, initially set as dry (data not shown). 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 (data not shown).

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 and diffusion rate (water transfer from the water table to the river), it was possible to make the water-table level coherent with 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. Figure 6 shows the variations in water levels in the six water-table tanks of the model along the year. An initialization artifact consists in 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 MAS approach to create our model, it doesn't include any autonomous agent able to make decisions yet. At the present stage, 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 water-stress threshold. As precise information on RLR wilting point in the Huay Bua watershed is not available, this value is arbitrarily set to field capacity. At each time step, the function "evaluate water stress" calculates the proportion of water-stressed fields that could not be watered because of insufficient water volume in the ponds or in the rivers or because they are located too far from these 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. 7A). 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 7B 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 to allow ponds to refill.

Discussion and conclusions

These simulations illustrate the dilemma that farmers have to face: early sowing and transplanting of RLR nurseries may be important for farmers who wish to sell a large share of their rice crop. At the same time, early sowing increases the risk of drought, which occurs frequently in the early part of the wet season. These first simulations show possible uses of the simulator and indicate that the small on-farm ponds are an efficient infrastructure to reduce the natural risk in RLR production. These findings confirm the relevance of the Royal Thai Government led project on small-scale irrigation in this region. This project opens new avenues for the intensification of agricultural production and for increasing the local employment of family labor.

The initial simulation results depend on parameters chosen during the model conceptualization. Their respective values were implemented in the model and corrected during the verification and calibration steps by relying on the “expert” knowledge of the modeler. These simulation results should be interpreted with care and must be further validated by presenting them to local farmers to assess their degree of correspondence with actual circumstances based on farmers’ experience. An increasing number of wells used for the irrigation of rice and vegetable crops were 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 water storage in small 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. One relevant topic to be explored with local communities would be the possibility of exploiting common water resources such as several large collective ponds that are currently underexploited.

When dealing with water management, socioeconomic dynamics must be taken into account and examined in interaction with biophysical ones. As the MAS offers an environment allowing the insertion of autonomous farmer-agent in the model, the next step in its implementation will consist in adding such agents making decisions regarding water use. This will allow the simulation of new scenarios in which farmer-agents could coordinate their actions and cooperate. Introducing different farmer-agents in the model will allow to model irrigation processes depending on individual decisions based on stakeholders’ perceptions of the water dynamics rather than using irrigation functions implemented by the modeler. A participatory modeling approach will be used to analyze stakeholders’ perceptions and to build a shared understanding of the water availability – water uses problem among them. Individual interviews, focused group discussions, and various mediation tools, such as role-playing games (RPG) and MAS simulations, will be used toward this end. The MAS model will be transformed into a RPG to be played with farmers to help them understand how it works, and the simulated results will be verified by presenting them to stakeholders. Simultaneously, new information gathered during the RPG and follow-up discussions with farmers-players will be added into the model as part of its validation by the stakeholders.

References

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

Barreteau O and F. Bousquet. 2000. SHADOC: a multi-agent model to tackle viability of irrigated systems. In: 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 Modeling 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.

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 (eds). Characterizing and understanding rainfed environments. Manila (Philippines): International Rice Research Institute. 111-130.

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. 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. 26-29.

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

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, (eds). Characterizing and understanding rainfed environments. Manila (Philippines): International Rice Research Institute. 75-95.

Office of Agricultural Economics (OAE). 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. Manila (Philippines): International Rice Research Institute. 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 February-5 March 1994, Lucknow, Utter Pradesh, India. 239 p.

Somrith B. 1997. Cultivar improvement for rainfed lowland rice in Thailand. In: Fukaï 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. 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. In: Irrig. Eng. and Rural Plan. No. 8.

Acknowledgments

The authors wish to thank the Faculty of Agriculture at Ubon Ratchathani University (UBU) and the National Research Council of Thailand (NRCT) for facilitating the implementation of this research.

List of figures

Figure 1.

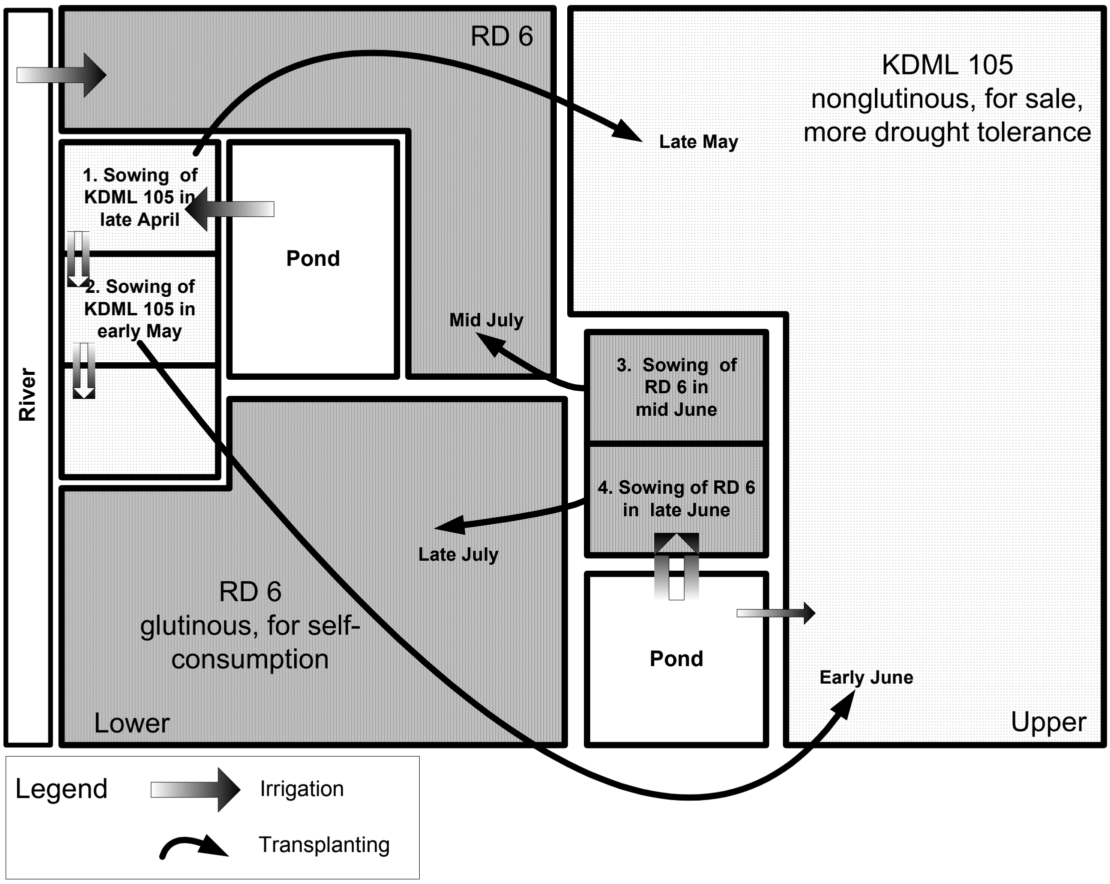
RD 6
KDML 105
nonglutinous, for sale,
more drought tolerance
Late May
1. Sowing of KDML 105 in late April
Pond
2. Sowing of KDML 105 in early May
Mid July
3. Sowing of RD 6 in mid June
4. Sowing of RD 6 in late June
Late July
River
RD 6
glutinous, for self-consumption
Pond
Early June
Lower
Upper
Legend
Irrigation
Transplanting

Figure 2.

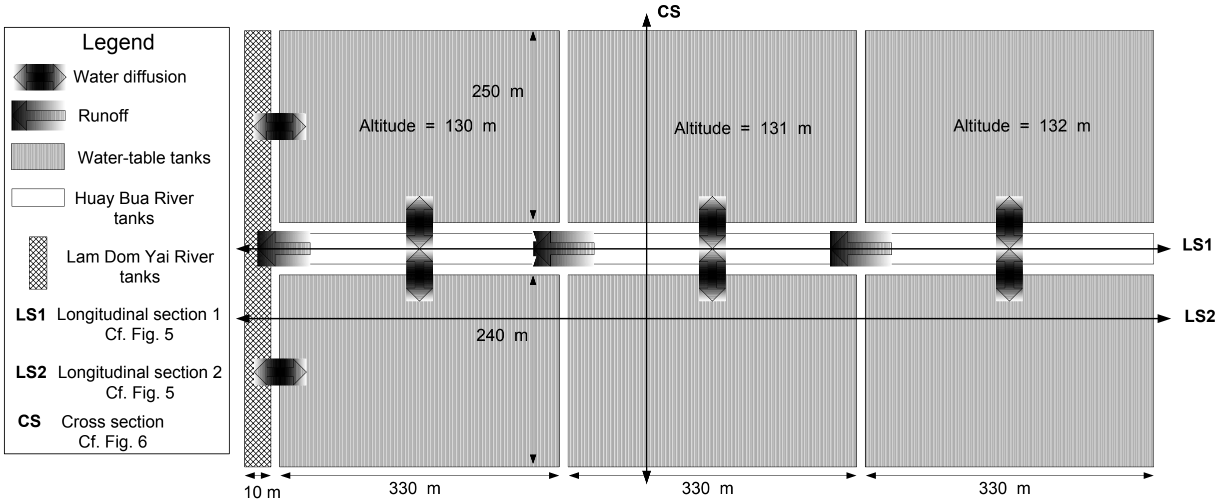

Figure 3.

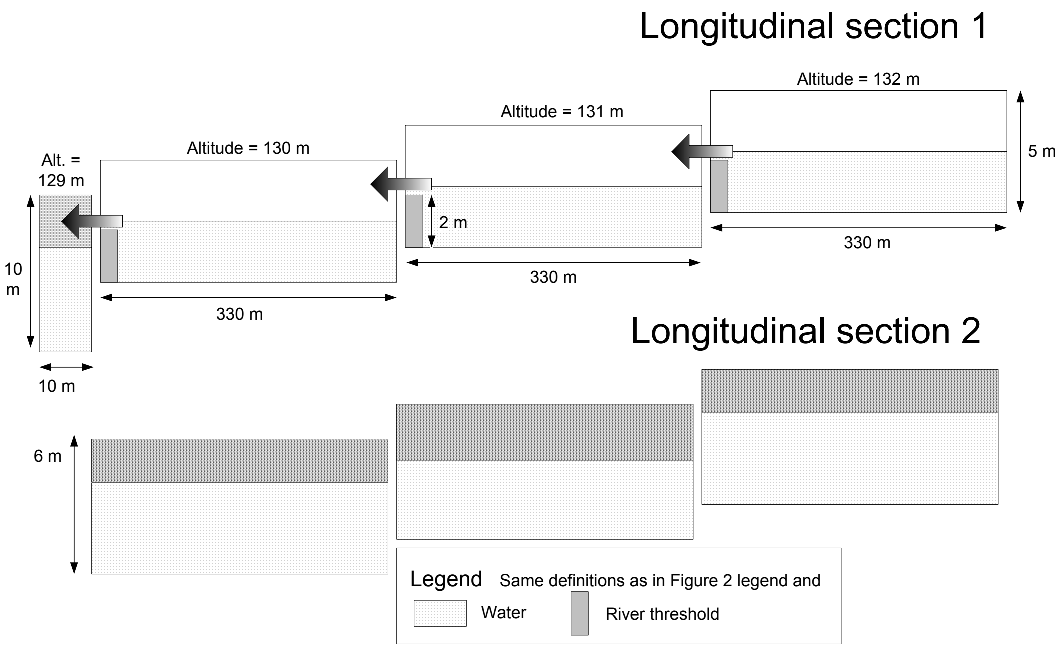

Figure 4.

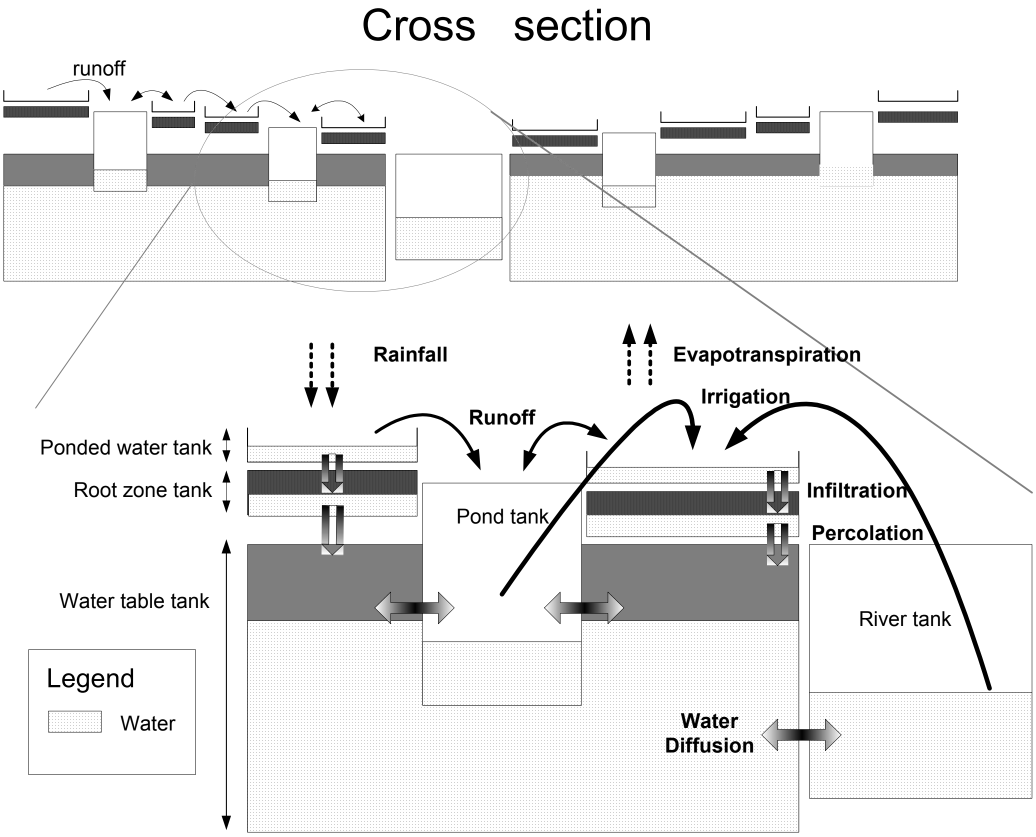

Figure 5.

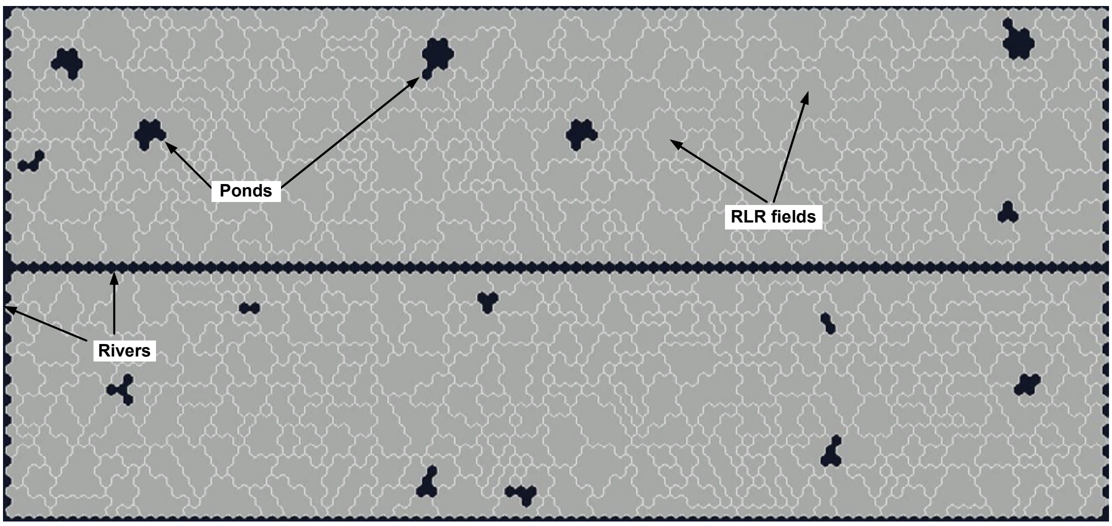

Figure 6.

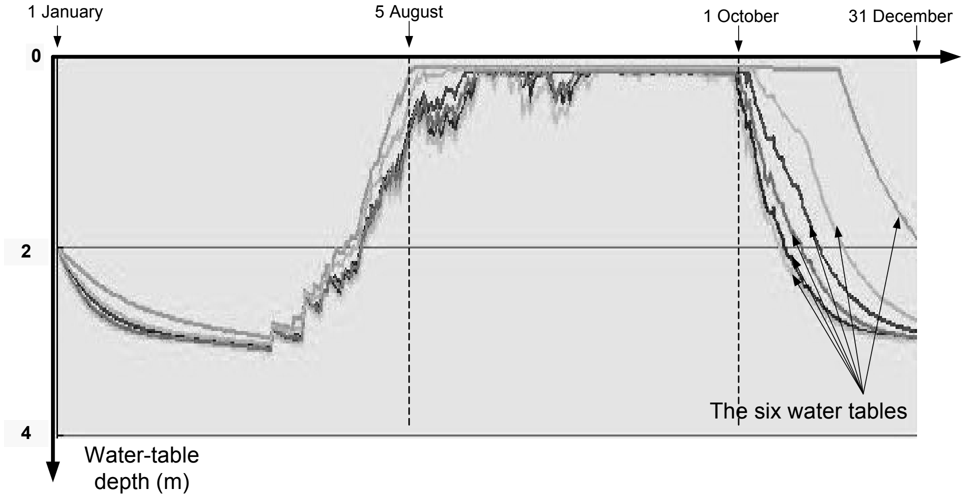

Figure 7.