A GIS-BASED IRRIGATION EVALUATION STRATEGY FOR A RICE PRODUCTION REGION

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ABSTRACT

Water shortage has become an international problem and this is especially true in China. This paper will detail the process of constructing a GIS-based information system to complete large-scale evaluation for water irrigation efficiency in a rice production region in China. A GIS-based system is built to integrate evaluation models and manage irrigation region actively and present the evaluation result in this paper. The research region is divided into several sub-regions and each sub-region is irrigated differently. After comparison of the results of different irritation methods, the suitable way of irrigation for a certain region can be selected. In this study, each rice production farm field located in sub-regions will be regarded as a basic unit and is digitalized to form spatial database. We monitor all growing stage of paddy rice and record water irrigation and rice yield. The goal is to find region-fit irrigation strategy and thus to enhance the profitability of irrigation water.

INTRODUCTION

Lack of available water resources in most countries is increasingly becoming a serious problem. Development of industries and agriculture thus have been severely limited by the shortage of available water and will be even more serious in the near future if no effective measures are taken. As the world population is still increasing, food security is challenged by large food demand and threatened by declining water availability. Take Asia as an example, to keep up with population growth and demand for food (Pingali, 1997), it is estimated that rice production has to be increased by 56% over the next 30 years (IRRI, 1997). At the same time, waste of water resources in agricultural irrigation is still serious, however, agricultural irrigation in rice production has the potential to be improved. In Asia again, irrigated rice accounts for about 50% of the total volume of water diverted for irrigation (Guerra, 1998). In many Asian countries, per capita availability declined by 40±6.0% between 1955 and 1990, and is expected to decline further by 15±5.4% over the next 35 years (Gleick, 1993). This situation is further aggravated by dramatically increasing costs for irrigation development over the past decades. Because of the combined increasing demand for food with the increasing shortage

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of water, rice producers face three major challenges (Belder, 2004). Research and development of a water-saving agriculture in paddy rice is an important way today to make agriculture and industries sustainable in terms of water consumption. The traditional irrigation system of rice production is transplanting in a field that is kept continuously flooded throughout the growing season. This is called flooded irrigation. Land preparation consists of soaking, ploughing and puddling (i.e. harrowing until a soft muddy layer of 100±15mm is formed in saturated conditions). The water requirement for land preparation is theoretically150±20mm, but can be 5 times higher when its duration is long (De Datta, 1981; Bhuiyan, 1995). Evaporation, transpiration, and Seepage and Percolation (SP) are the main outflows of water from a rice field. SP rates depend on the hydraulic properties of the soil, water pressure heads, and the length and state of the bunds (Wopereis, 1994). It has been estimated that SP accounts for 50±8.0% of the total water input to the field, and most field-level water-saving strategies concentrate on the reduction of SP flows (Tabbal, 2002). In support of water-saving efforts, Different farm-level technologies to save water were experimented to increase water productivity. Since the term “water-saving irrigation techniques” been introduced (Guerra, 1998), many irrigation systems in rice production have taken aim at reducing SP rates by reducing the depth of flooded water, keeping the soil just saturated or alternate wetting/drying, i.e. allowing the soil to dry out to a certain extent before re-applying irrigation water.

GIS technology has come a long way in the past decade and continues to evolve, with the basic function being spatial data management. New application areas have been found, including agriculture, forestry, hydrology, resource management, and coastal resource management. Those areas benefit much from the development of GIS. In addition, new products have appeared in the marketplace. What is more, dramatic improvements continue in the capability of hardware and software operating platforms; and many large data sets have become available. GIS technology has grown rapidly to become a valuable tool in the analysis and management of spatial ecological problems. It is not new for GIS to be used in agriculture. Since the Canada Geographic Information System or CGIS, generally acknowledged as the first GIS system, GIS has been applied by resource planners and decision-makers with a set of tools to analyze spatial data effectively. Agricultural resource planning, and land assessment are also among the areas that GIS can provide benefits. These areas can be classified as macro applications since large areas are usually covered. A more popular application of GIS in agriculture, which may be classified as a micro application nowadays is precision agriculture, tailoring soil and crop management to fit the specific conditions found within a field with the aim to improve production efficiency and/or environmental stewardship.

After a literature review and analysis, this study focused on comparison of different water-saving irrigation techniques at the field-level. The main objective is to find a suitable irrigation method and thus to formulate a suitable irrigation system for our research region with the aid of GIS.

METHODOLOGY

Research Region

The central theme of this paper is investigating farm-level water irrigation with different strategies, i.e. water-saving strategy and flooded irrigation. We select an agriculture production base in Jingmen city as the experiment base. Located in the Hubei Province, China, with 112.11 east longitude and 30.52 north latitude at an altitude of 100 m, Jingmen City has a total land area of nearly 800 km^2. Most of the area for agriculture production covers the suburb region of the city. The semitropical climate of the city meets required living conditions of paddy rice. The experimental site was surrounded by lowland rice fields in the 160,000 ha irrigation system. The soil texture was silty clay loam.

Experiment design

Agriculture production is a spatial ecological system that shows uncertain, fuzzy characters in management. To get maximal benefit and minimal side effect, it is necessary to test management method on different agriculture farm field to get the most suitable irrigation system. There are two kinds of agriculture field model: regular grid field in precision agriculture and irregular field grid typical in rugged regions. Precision agriculture usually regularly partitions a large area into groups of small cells (Figure. 1 (a)). In practice, however, it is almost impossible to get regular farm field due to scatted farm location and rugged land (as in mountainous region). Figure 1 (b) shows decision-making grid for large-scale farm-level fields. Those fields are irregular, scatted and ill shaped. Because of this fact, it is much more complicated for farm-level agricultural field management than that for digital agriculture because the diversity of living conditions for crop should be considered when decision on field management is made. So we select a relative flat study region and design two water-saving irrigation systems to investigate the effect of saving-water irrigation strategy compared with the traditional flooded irrigation system.

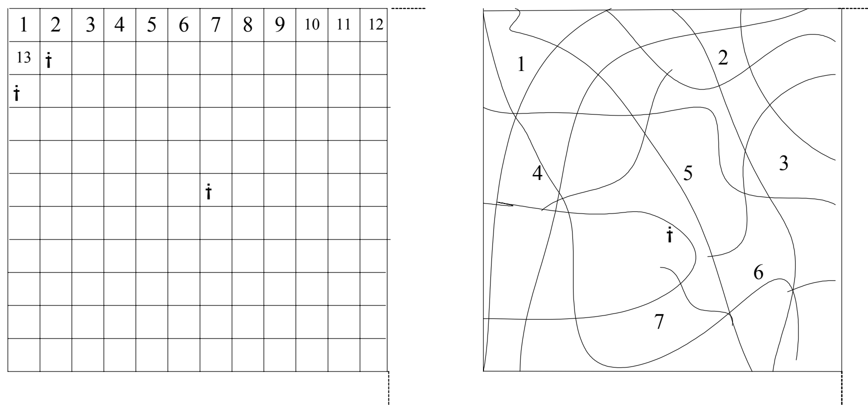
The designed irrigation systems adopted in this study include the traditional irrigation and two types of water-saving irrigation as shown in Figure 2. The whole stage of rice growth can be divided as vegetative, reproductive and ripening periods. Table 1 gives the cropping calendar for the experiments. Irrigation treatment in different stage is varied for all the irrigation strategies. For the traditional irrigation (signed as TM2), much of the time during the growing period rice is covered by irrigation water. This way is also called flooded irrigation. Compared with this traditional way, water-saving strategies is much different. The TM1 and TM3 in Figure 2 represent two types of water-saving irrigation. It can be seen that alternative irrigation is conducted for the whole growing stage with TM1. Alternative irrigation is conducted for the first part of growing period and shallow saturated irrigation is conducted in the following period with TM3. Figure 3 is the outline map of the experiment base. The whole research region is divided into 3 sub-regions and each sub-region is composed of numerous farm fields. Three types, i.e. TM1, TM2 and TM3, of irrigation strategy are conducted in different fields randomly, belonged to the three sub-regions respectively. Soil property of each farm field is similar so the factors that affect yield can be neglected. And the rice plants are specifically prepared before transplanting to ensure the least difference for each treatment. Monthly rainfall, temperature and radiation are recorded as shown in Table 2. The shape of each field is digitalized by GIS software and GIS can easily calculate the area. We monitor all growing stages and record the rice yield and water consumption for each field and compare the difference of irrigation treatments. The average yield and water input per hectare is calculated to evaluate the effect of different irrigation methods with evaluation models of water efficiency organized in different ways.

Table 1. Cropping calendar for the experiments

Experiment	Sowing	Transplanting	Panicle initiation	Flowering	Harvest
Date	18 April	20 May	6 July	8–12 August	6–11 September

Table 2. Monthly rainfall (mm), mean maximum temperature (˚C), mean minimum temperature (˚C), and mean daily radiation ($MJm^{-2}\ d^{-1}$)

Month	Rainfall	Tmax	Tmin	Radiation
May	162	27.4	15.3	18.5
June	153	27.9	21.6	17.4
July	94	30.5	23.7	19.2
August	52	30.8	23.4	19.9
September	50	29.5	20.9	17.1



(a) Regular grid in digital agriculture (b Irregular farm-level field distribution

Figure 1. Comparison between two kinds of agriculture field model

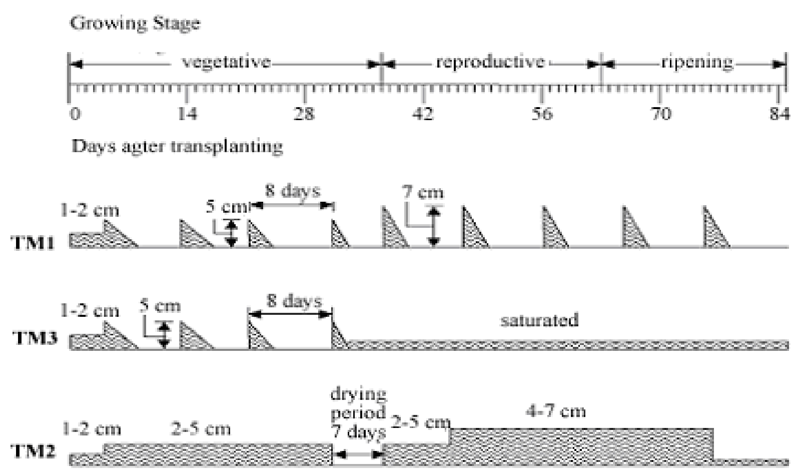


Figure 2. Irrigation design: water-saving treatment (TM1 & TM3) and flooded irrigation (TM2)

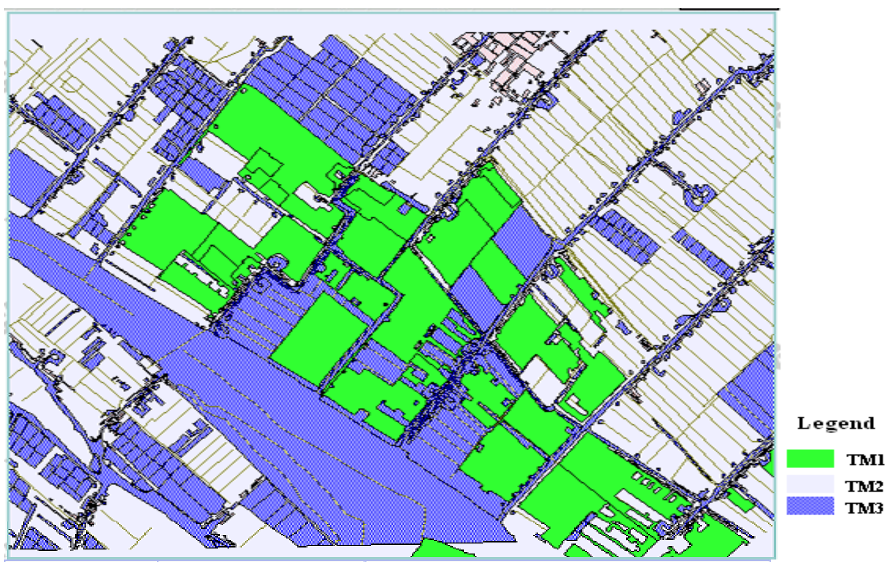


Figure 3. Experiment design: water-saving irrigation & traditional flooded irrigation

Basic software and evaluation process

To actively manage the experiment site, we design a GIS-based software named Irrigation-GIS to monitor the whole region. It is actually a web-based rice production experts to assist the farmer in irrigation, fertilization and other management issues. Three layers, viz. data layer, application layer and browser layer, logically composes Irrigation-GIS framework (Figure 4). This multi-layer structure makes the system maintenance easier and the service range wider.
The first layer, also called presentation layer, is used to communicate with users by various web interface elements known as graphic user interface or GUI. Anyone who can connect to the Internet can be authorized to use the system and aid management of the farm fields in any place at anytime through GUI of the system. So it is easy to input or get data remotely. GUI is built in dynamic Java Service Page or Jsp, so that it can be used over the Internet (or any other large network) without other additional requirements for the client computer but general website browser software, such as Internet Explorer or Netscape. This is the browser layer.
The second layer is the key component that supports the whole function of Irrigation-GIS, including problem interpretation, operation control, knowledge reasoning, model realization and their integration in problem solving. This layer forms the web pages that will forward to browser layer dynamically or statically. These web pages either accept data from the browser or forward analysis result to the browser. The accepted data then will serve as parameters of analysis models, conditions for irrigation affecting evaluation process or basic information for GIS. The evaluation model syntax/implication interpretation module will be triggered and interprets the input parameter value to choose and forms a suitable model or

models the complete numerical calculation. Similarly the evaluation model formalization/resolution constructor will interpret some input data to form conditions for model parameter input. As for GIS functions, the input data also includes spatial information as farm field ID, soil type relating to the field, etc., so GIS will locate and produce a map-based analysis result to users with the help of model analysis and GIS spatial analysis modules. In order to get map-based analysis result, Esri's ArcIMS 4.0 is used as WebGIS engine. ArcIMS supports java connector that passes request of java-program to the spatial server and thus generates the result expressed in map. All these processes are universally controlled by the controller component. The controller component is also responsible for interaction with system data through data access interface Jdbc. The bottom layer is system data. Here the system data represents evaluation models, knowledge and spatial database as well. Spatial data are those data that are geo-referenced and can be accessed by SDE API offered by Esri's ArcSDE 8.1 while non-spatial data are accessed by Java DataBase Connectivity (JDBC). Evaluation models are represented in Objected-oriented frame and can be constructed dynamically at system run time. All parameters and syntax/implication interpretation used in models as well as spatial information are stored and retrieved by the database. Figure 5 demonstrates the three layers and shows the logical design of irrigation-GIS. Users interact with the key components (including application server and database server) through mobile devices or browsers using Extensible Markup Language (or XML) protocol.

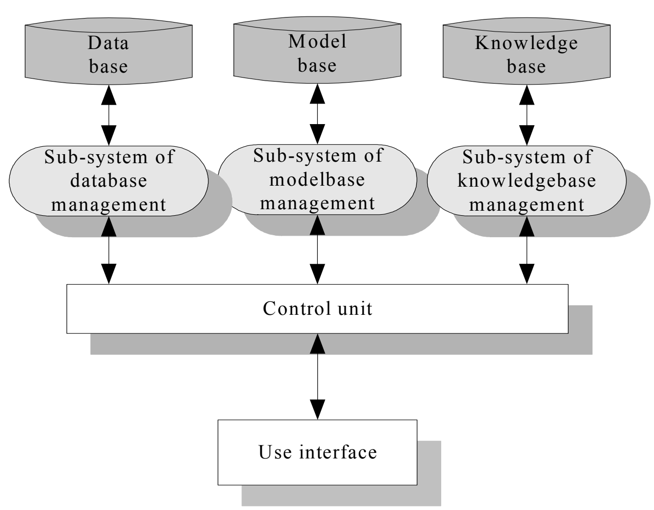


Figure 4. Key components of Irrigation-GIS

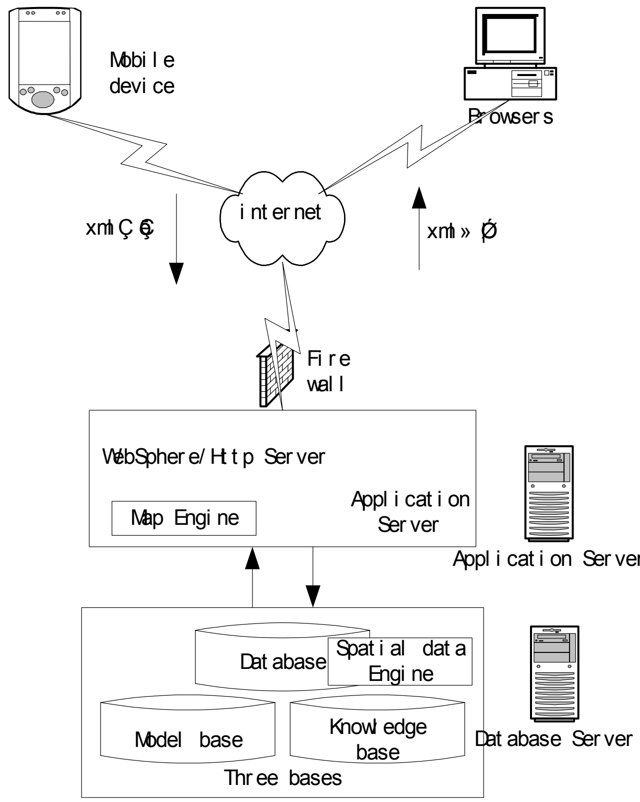


Figure 5. Logical design of Irrigation-GIS

ANALYSIS OF RESULTS

GIS is used as a tool to manage spatial data. GIS gives a clear and active map as water input or grain yield distribution that can help to find valuable rule of different irrigation systems. The area of each experiment field can be calculated easily be GIS and the data of all farm fields experimented can be managed by GIS and displayed in the form of map. What we care most is all water input and the ultimate grain yield for different farm fields. And the average water input and grain yield of different irrigation strategy are summarized. Though all stage of rice growth was monitored and the dried bio-mass was weighed, as for this study, we just want to compare the efficiency of water use in irrigation. Table 4 shows the total average irrigation water input. The water input in TM1 averaged 392 cubic meters per hectare. This is also the traditional irrigation method (TM2). Obviously this irrigation strategy wastes water. Contrary to TM2, TM3 has the least water input, averaging only 326 tons per hectare. Compared with TM2 and TM3, alternative irrigation (TM1) stands on the middle in terms of water input. Then we compare the average grain yield of different irrigations (Table 5). It can be seen that alternative irrigation (TM1) ranks at the top with a grain yield of 8.4 tons per hectare. Flooded irrigation, with the average yield of 8.1 t/ha, follows TM1. Alternative-saturated or TM3, though with the least of water input, has the least grain yield. So we can conclude that least water input of irrigation treatment may not be the case with least grain yield and the largest water input of irrigation treatment may not be the case with largest grain yield either. There may exist a balance for grain yield and water input.

The grain yield for water input can also be analyzed here. It can be found that traditional irrigation has an average of 20.1 grain per kg water. Similarly TM1, i.e. alternative irrigation strategy, has an average of 25.1 grain per kg water and TM3 is 23.6. As for water use efficiency, it is obvious that alternative one (TM1) has the top value and is our recommended irrigation strategy for this region.

Table 4. Average irrigation water inputs ($\times 10^3$ kg ha−1) in the experiment

Experiment	Flooded irrigation (TM2)	Alternative (TM1)	Alternative-saturated (TM3)
Water input	392 ± 62	334 ± 94	326± 20

Table 5. Average grain yield ($\times 10^3$ kg ha−1) for the experiments

Experiment	Flooded irrigation (TM2)	Alternative (TM1)	Alternative-saturated (TM3)
Grain yield	8.1 ± 1.2	8.4± 2.1	7.7± 0.9

CONCLUSION AND DISCUSSION

Water shortage has become an international problem. Scientists are trying to find effective ways to improve water use efficiency. Agriculture irrigation takes a great part of water use and waste of water in irrigation is easy to see. So, finding and evaluating an irrigation system for a certain region is important. GIS originally is developed to store, retrieve and display spatial data and domain models are combined with GIS to simulate some complex phenomena later. The use of domain models in GIS greatly expands its application domain and improves its application level. Applications such as environmental pollution simulation, shortest route selection and material distribution plan, flood submersion prediction, etc are benefited a lot from GIS and domain models. Some special spatial tasks are beyond either GIS itself and can be solved by domain models. This put GIS use in wide applications. The integration of GIS and evaluation model of irrigation effect is our research consideration. The advantage of GIS and evaluation model integration is its power to support people in decision-making with reliable and comprehensible map-based format. The critical factors in this integration include evaluation model construction, model organization, the integration of GIS models and spatial data, and the proper use of model and spatial data.

The fact is that the topologic features and uneven surface of agricultural land in most regions makes farm fields small in area, irregular in shape, and scatted in distribution. The overpopulation makes this even worse since a large farm field usually has to be divided into bits and pieces to meet all farmers need for sharing. This is particularly true in China and many overpopulated countries. The mode of digital agriculture that a large land evenly partitioned into regular grid is inapplicable in those regions. Moreover models are the main component that calculates fertilizer, water and pesticide application for different grids while expert knowledge is usually fixed in models. Knowledge lacks flexibility in maintenance. This also limits the extension of GIS use. The approach discussed here for using farm fields (grids) variability information and expert knowledge for enhancement of yields and reduction of risk in farm field management should be applicable over much of those regions. To offer an application system accessible to location-distributed users, a web-based spatial decision system with the integration of GIS models (irrigation effect evaluation) and spatial data (the farm field distribution), Irrigation-GIS is developed. Farm fields associated with paddy rice are digitalized and evaluation models for irrigation effect are constructed that can serve as the basic data to evaluate and compare agriculture water profit. It will lead to appropriate field management in irrigation to any farm field and guide us to better the use of water in irrigation. The novelty of Irrigation-GIS is its integrated evaluation models of irrigation that contains information on most of agronomic knowledge. With the system run, it is possible to tap the complex spatial decision-making and gain an insight into the variety of options of management practices of water irrigation suitable for each piece of farm fields. This paper presents water irrigation for rice field with the aid of GIS and a Web-based software Irrigation-GIS is built to support the process.

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