

Cellular automata and GIS based landuse suitability simulation for irrigated agriculture

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Abstract: Cellular automata (CA) is increasingly used to simulate various dynamic courses, e.g. urban spatial growth, forest fire spread and soil desertification. CA simulates these courses with iterative evolutions. Through simple and partial rules to form complex space structures and patterns, CA can express complex systems which are difficult to perform only with mathematical formulas. In combination with GIS Software, such as ArcGIS, it can directly and vividly reflect the geospatial state changes and accomplish many kinds of spatial analysis. This paper introduces CA concept into irrigated agriculture and presents a new CA based GIS (Geographic Information System) approach which incorporates simulation methods and implementation of land suitability evaluation to assess agriculture land use in a GIS environment.

In this paper, multi-criteria evaluation (MCE) methodology is utilised to deal with data relating to the environmental conditions in the study area, the Macintyre Brook Catchment, southern Queensland, Australia. The data include soil, topography, landuse, surface and groundwater attributes. Each criterion is processed with a specified method and forms one criterion layer. These criterion layers are regarded as the initial irrigated agriculture conditions in the CA generation courses. They are weighted using an Analytical Hierarchy Procedure (AHP) approach, which is a well-known method of MCE, before being integrated to generate a temporary baseline suitability layer which becomes conditions for the next course of CA generation. The generation courses proceed step by step and each temporary suitability layer is based on the layer which was previously generated. With CA spatial simulation of this kind and essential statistical selection, the resultant suitability layer could be built. All these data processing and modeling procedures are incorporated into a GIS framework. This framework is developed and implemented as a tool, called AHP-CA-GIS, using C#.NET computer language. In this tool, MATLAB software embedded components are adopted for computing AHP matrices, CA simulation is performed, in evaluation procedures, and ArcGIS Engine 9.2 development components are applied to complete spatial modeling tasks.

The resultant land suitability map of AHP-CA-GIS simulation is derived from the last course of CA generation with a predefined judgment rule of evolution steady state. It represents land use suitability potential for irrigated agriculture of the catchment, which can help the stake-holders make better landuse planning decisions. The tool is developed with high applicability and flexibility. Some adjustable parameters are open which allows users to rectify the modeling inputs so as to adapt to different scenarios. It increases the scope of application of the GIS simulation and makes it practical for decision-making.

Keywords: *Cellular automata, GIS, Suitability Simulation, Irrigated agriculture, Multi-criteria evaluation, Analytical Hierarchy Procedure*

1. INTRODUCTION

Land suitability evaluation defines suitability of certain kinds of landuse based on natural and socio-economic attributes. It is the fundamental work and an important content of overall landuse planning, which requires a scientific approach to guide development, avoid errors in decision-making and over-investment, for sustainable utilization of land resources.

Multi-criteria evaluation (MCE) is a widely used methodology to handle land suitability evaluation (Tiwari *et al.*, 1999). It is primarily concerned with how to combine the information from several criteria to form a single index of evaluation. The Analytical Hierarchy Procedure (AHP) method (Saaty and Vargas, 1991) is a well-known method of multi-criteria technique. This approach of decision making involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives. It is especially useful in situations where it is impractical to specify the exact relationships between large numbers of evaluation criteria (Chen *et al.*, 2009). Geographic Information System (GIS) is a computing application capable of creating, storing, manipulating, visualizing, and analyzing geographic information (Goodchild, 2000). Integration of multi-criteria evaluation and GIS is popularity these years (Makropoulos and Butler, 2005; Malczewski and Rinner, 2005; Boroushaki and Malczewski, 2008) in natural and social research.

The integration of GIS and multi-criteria evaluation methods has powerful spatial analysis functions. But previous studies (Store and Kangas, 2001; Giordano and Riedel, 2008) mainly concentrated in buffer analysis, overlay analysis, network analysis and other static analysis tools. GIS alone often seems powerless in complex system modeling and simulation. Therefore, many have applied cellular automata (CA) theory which is one kind of geographic simulation methods. (Wu and Webster, 1998; D'Ambrosio *et al.*, 2001; Ménard and Marceau, 2007; Yang *et al.*, 2008; van Vliet *et al.*, 2009). CA is a discrete model studied in computability theory, mathematics, theoretical biology and microstructure modeling (Wikipedia). It consists of a regular grid of cells, each in one of a finite number of states. The grid can be in any finite number of dimensions, generally two dimensions. Time is also discrete, and the state of a cell at time *t* is a function of the states of a finite number of cells (called its neighborhood) at time *t*-1. These neighbors are a selection of cells relative to the specified cell. Every cell has the same rule for updating, based on the values in this neighborhood. Each time the rules are applied to the whole grid a new generation is created. It has been proven that cellular automata approach is an effective way to simulate complex geo-spatial systems (Golaes and Martinez, 1999). However, in landuse suitability assessment, especially in agricultural irrigation suitability evaluation, CA has not been applied till now.

This paper applies CA to MCE, in combination with AHP in ArcGIS environment to assess agricultural irrigation suitability for an experimental area. A tool called AHP-CA-GIS has been designed and developed to help in the simulation process. The optimal result map is selected to represent the spatial suitability distribution of the study area so as to support decision-making and reasonable resources allocation.

2. METHODOLOGY

2.1. Study area

The Macintyre Brook catchment is located in southern QLD near the state border with NSW, and lies between 27°57'01''S and 28°47'48''S latitude, and 150°45'05''E and 151°42' 24''E longitude. The catchment is relatively flat in the western area, with undulations becoming steeper towards east and northeast. Macintyre Brook flows from east to west, and its tributaries are the main source of surface water for the region. Coolmunda Dam supplies irrigation water to Macintyre Brook along which the main irrigation areas of the catchment are located (Chen *et al.*, 2009).

The catchment covers an area of 4,200 km². It is characterised by extremely diverse soil types and topography (Harris, 1986), making it suitable for a wide variety of landuse (Figure 1) and rural production.

Currently about 1.5 % of the catchment area is devoted to irrigate cropping and perennial horticulture, as well as sown pastures. The remainder is dominated by dryland cropping (3%), native pasture grazing country (80%) and State Forest Reserves (15%). (Chen *et al.*, 2009). Detailed description about the catchment can be found from Chen *et al.* (2009).

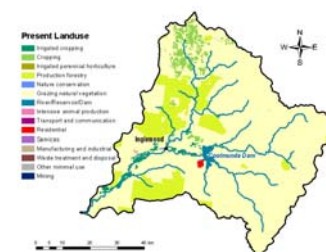


Figure 1. Macintyre Brook landuse map at 50m resolution (Chen *et al.*, 2009).

2.2. Derivation of criterion maps

The derivation of criterion maps comprises three steps:

- Suitability classification

This study uses the suitability classes which have been proposed by FAO (1976) consisting of four levels. They are stated as: highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and unsuitable (N).

- Selection of criteria

Seven criteria have been chosen which include slope (S), soil texture (ST), depth to water-table (DTW), electrical conductivity of groundwater (ECw), hydraulic conductivity of soil (Ks), distance to stream (DS) and irrigation landuse (IL). The criterion IL describes irrigation distribution with binary values. The threshold values for the rest are given in Table 1. They were determined based on literature survey and expert opinions, and are only applicable to broad scale analysis of irrigated cropping in the catchment.

- Generation of criterion maps

The criterion maps are in raster format with a cell of 100m x 100m. UTM Zone 56S has been used as the spatial reference. Based on the thresholds in Table 1, we classified criterion maps S, ST, DTW, ECw, Ks and DS into four classes. Raster layers have numerical values 4, 3, 2 or 1 which represent S1, S2, S3 or N. Initial IL was used to complete the implementation of CA algorithms. Each cell of it has the value 1 or 0, which represents whether it is an irrigated area or not (Figure 2).

Table 1. Criteria for suitability assessment (Chen *et al.*, 2009)

Criterion	S1	S2	S3	N
S (%)	0-2	2-4	4-8	>8
ST	fine to medium	heavy clay	coarse or poorly drained	very coarse or shallow depth
DWT(m)	>4	3-4	2-3	<2
ECw(dS/m)	0-0.5	0.5- 2	2-5	>5 (if depth<4m)
Ks (m/d)	0.3-1	0.05-0.3 or 1-2	2-2.5	<0.05 or >2.5
DS (m)	<1000	1000-2000	2000-3000	>3000

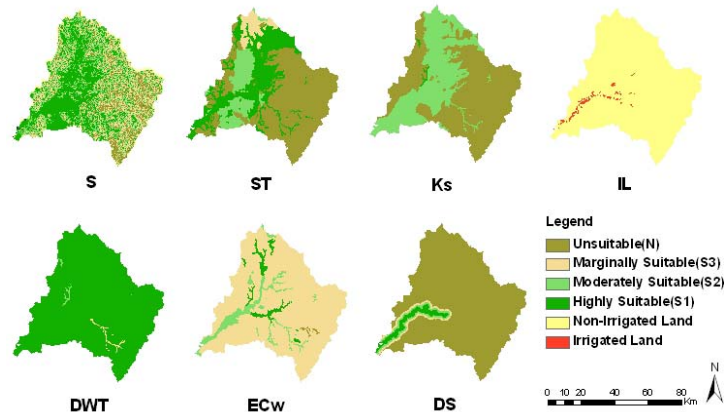


Figure 2. Criterion maps used for the evaluation of irrigated agricultural land. The suitability levels are classified based on the threshold values.

2.3. Determination of criterion weights

AHP is used to determine criterion weights. A pair-wise comparison matrix is created to express the relative importance between each two criteria. The comparison matrix is basically a list of criteria, which are weighted depending of their respective importance. The matrix values, which could be 1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8 or 9, represent the relative degree of importance of one criterion against another. A bigger matrix value means the first criterion is more important than the second one and vice versa. Value 1 means the two compared criteria have equal importance. Value 9 represents absolute importance and 1/9 the absolute triviality (Saaty and Vargas, 1991).

2.4. Process of AHP-CA-GIS Simulation

After the AHP process, all weighted criterion maps were input into the AHP-CA-GIS model in which MCE is executed to simulate irrigation suitability evaluation. The model prescribes that the state of a cell in time t+1 is determined by its state and its neighbors in time t as well as corresponding conversion rules. In the process of simulation, landuse development intensity is obtained through a 3 x 3 window, nine cells in total, that is, return a value for the central cell which indicates the proportion of development of its eight neighbors. With the probability methods, transform rules can be defined flexibly. The state at time t+1 can be determined by:

$$S_{xy}^{t+1} = f(P_{xy}^t) \tag{1}$$

In this formula, S_{xy}^{t+1} is the landuse state in the location (x, y), time t +1. P_{xy}^t is the conversion probability of state S in location (x, y), which could be represented as (Wu and Webster, 1998):

$$P_{xy}^t = \phi(r_{xy}^t) = \exp[\alpha(\frac{r_{xy}^t}{r_{max}} - 1)] \quad (2)$$

where r_{xy}^t is the estimated conversion intensity of state S in location (x, y); α is the discrete parameter, which has the value between 1 and 10. The value of α governs the stringency of suitability estimation, with a higher value reflecting a more stringent estimation process. Thus, this parameter has an important influence on the whole estimate pattern. r_{max} is the maximum value of r_{xy} . In this paper, the specification of r_{xy}^t becomes:

$$r_{xy}^t = (w_1S_{xy} + w_2ST_{xy} + w_3DTW_{xy} + w_4ECw_{xy} + w_5Ks_{xy} + w_6DS_{xy} + w_7IL_{xy})Restrict_{xy} \quad (3)$$

where w_1, w_2, \dots, w_7 are AHP weighting parameters, $S_{xy}, ST_{xy}, DTW_{xy}, ECw_{xy}, Ks_{xy}, DS_{xy}, IL_{xy}$, respectively, are standardized values of each factor in location (x, y). $Restrict_{xy}$ is the total score for restrictive factors in location (x, y), which has binary value of 0 or 1 to indicate whether it has a restriction on suitability constraints. For instance, rivers, reservoirs and other protected areas should be treated as restrictive factors because the probability they develop into irrigation lands is 0.

When all the conversion probabilities of every grid positions have been obtained, the conversion probability matrix of next state is generated. Then a new fundamental layer is generated as input for the next state. Iterative runs are executed to make generations of conversion probability and probability map for irrigation suitability. From this map, in accordance with transform threshold $P_{threshold}$, an irrigation map of the next state is created. In the case of $P_{xy}^t \geq P_{threshold}$, if it is not irrigated land previously, it will convert into irrigated agriculture land; otherwise it does not change. In the case of $P_{xy}^t < P_{threshold}$, if it is irrigated land previously, it will convert into non-irrigated land; otherwise it does not change.

It should be noted that, simulation time has no necessary correspondence to real time (Cecchini, 1996). In this study, the generated irrigation landuse maps by iteration are not mapping into real time. With sufficient time-serial data, each criteria layer of real-time could be input corresponding to a specified iteration. This will be studied in the later research. There are two methods which terminate CA evolving and get steady suitable distribution. Firstly, compare two layers of time t and t+1. If there are no differences between these two layers, it means steady state has been reached. Secondly, expert picks eligible result with experience or preset limitation (threshold). The first method is used in this study.

3. IMPLEMENTATION OF THE INTEGRATED SIMULATION

3.1. Key Technology in Development

A tool is developed using C#.Net to construct the framework of the simulation software for suitability evaluation. MATLAB software embedded components are used to implement AHP and calculate criteria, weights. ESRI ArcGIS Engine, which is a core set of cross platform ArcObjects components compatible with multiple APIs (Application Programming Interface) (ESRI, 2008). is employed to read the raster layers, generate new raster files and present the simulation results.

3.2. Simulation Implementation

The implementation of the whole simulation software is expressed through Figure 3. It follows the course of CA evolution and is a process of space iteration.

1. Input AHP comparison into an Excel file with the same format to Figure 4c, so the tool can read the matrix, calculate and return the weight values of all criteria.
2. Create a restriction landuse map (Figure 4b) with the information extracted from present landuse data, in which restricted areas are in yellow and non-restricted areas are in green. It acts as a filter to exclude area where irrigation will not occur;
3. Input IL map. Generate a virtual intensity map which derived from IL map according to eight-neighbor CA rule for landuse development intensity mentioned in section 2.4. It indicates the probability of a particular land for irrigated agriculture;
4. Read cell values of criterion maps, restriction landuse map and intensity map in matrixes; input these values and corresponding weights obtained from the AHP into the AHP-CA-GIS model, and output the suitability probability matrix;
5. Generate the probability layer from the probability matrix, and then standardize the probability layer into a suitability classification layer;
6. Compare this suitability classification layer with the simulated layer from the previous generation course. If there are differences between these two layers, it means the steady state has not been reached, and the CA process needs to be further evolved. (If it is the first course, then it assumes steady state has not been reached). Based on the transform threshold described in section 2.4, a supposed irrigation landuse map was generated. The supposed map is generated based on an assumption. It is that irrigation will be developed on all highly suitable lands which will also be regard as a new condition layer to replaces the previous irrigation landuse map and then go back to repeat the process from Step 3 to Step 6. A series of iterations will be implemented until spatial distribution of suitability achieves steady state;
7. Based on field survey and expert opinions, judge that if the suitability map is satisfied for the decision-making demand. For example, if the high suitable region is too large that it is rejected by field survey, it means the suitability map is not satisfied. Discrete parameter α mentioned in Section 2.4 or AHP matrix values have to be adjusted as new inputs and execute step 1 to 6 again to generate a more reasonable scenario.

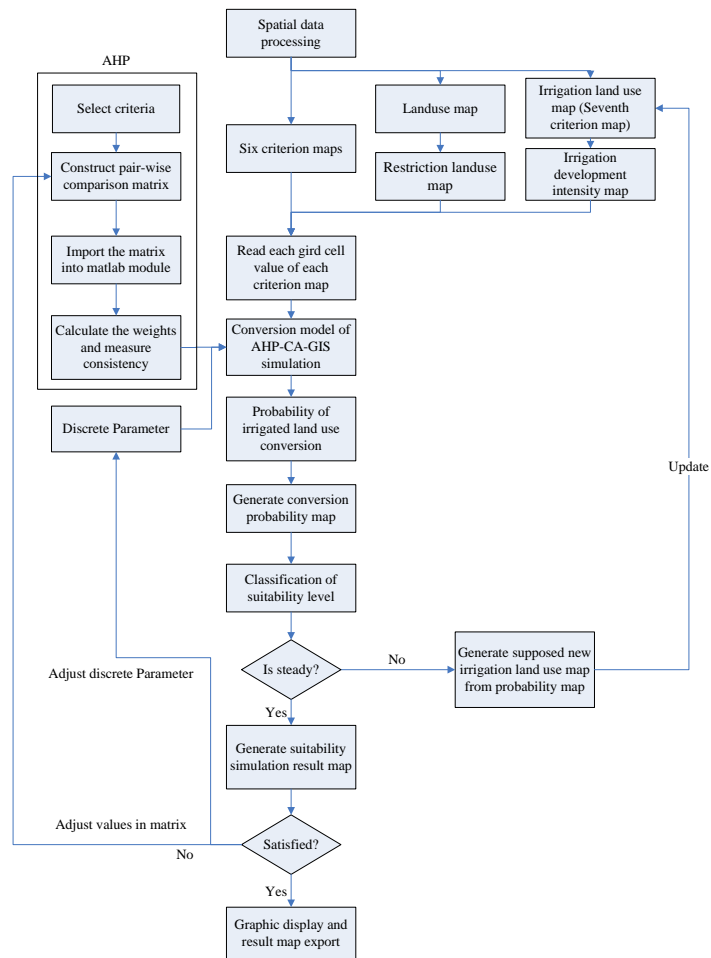


Figure 3. Workflow for implementation of simulation process.

3.3. AHP-CA-GIS Simulation Tool

Figure 4a shows the main interface of the tool with map control and layer control. Figure 4b presents the menu of “Process”. Figure 4c provides the AHP calculation interface after selecting “AHP Calculation” menu which shown in Figure 4b. The input matrix is read from an Excel file which stores the AHP comparison matrix of factors. With “Calculate” button clicked, weights for criteria will be calculated and shown in the result textbox (Figure 4d). In “CA Processing” panel, available weights and layers are listed. In “Develop intensity layer” dropdown list, select irrigation land use layer as input file, then input “Discrete parameter” defined in section 2.4, “Run steps” define the iteration times and “Transform probability threshold” given in section 2.4. When all the parameters have been configured, click “Run” button to start the process (Figure 4e). For the convenience to the users, the parameters can be changed easily to set up different

scenarios for testing and analysis. After iterative runs, the tool gives corresponding generated simulation result (Figure 4f).

3.4. Suitability Simulation Result and Discussion

With different input parameters, AHP-CA-GIS simulation tool can generate various simulation results. Figure 5 is the selected suitability evaluation map used in this study based on expert knowledge and field investigations. In this figure, about 4% areas of the total catchment are classified as S1 areas, about 9% as S2, 32% as S3 and 55% as N. S1 regions are mainly distributed on the flood plain of the Macintyre Brook where the water resources and soil conditions are better. N regions are mainly located in the south-east areas in the catchment which are characterized with complex topography and relatively steep slopes. They are also located in the regions with poor soil texture and lower hydraulic conductivity, and in regions where land uses have a small probability of converting into irrigation land.

Using GIS overlay analysis, present irrigated land was compared with the simulated highly suitable regions (S1) where irrigation development could occur with the greatest possibility of availability of water. The result showed that only 26% of the highly suitable lands have been developed for irrigation. It revealed the development potential of the area. The spatial distribution of suitability has shown that the impact of EC_w and DWT to evaluation results is not pronounced. K_s has great impact on the simulation result. More than 90% of the S1 and S2 regions are located in the areas where K_s is within the range of 0.5 m / d to 2 m / d. Soil texture also has an obvious classification effect. More than 90% of S1 and S2 lands are located at regions with fine to medium soil texture. Overlay analysis also showed that about 90% of S1 and S2 regions are on surfaces with slopes less than 2 degrees. Taking into account the requirement and availability of surface water for irrigated agriculture, we selected downstream parts of surface water which seldom run out of water in dry season and generated the DS criterion map. The highly suitable areas and the buffer areas in the DS criterion map have similar spatial form. About 70% of S1 areas are within 2000 meters away from selected parts of the stream.

It is evident that, with satisfied budget and water supply, the catchment has potential to expand its irrigation areas and provide more food supplies. Local decision-makers can make use of the study result, while also take consideration of political and economic factors, to determine the expansion of irrigated agricultural land.

4. CONCLUSION

As a new attempt to apply CA to agriculture, this paper introduced CA concept into suitability evaluation for irrigated agriculture. We integrated CA with MCE and GIS, and explored a new method of AHP-CA-GIS to implement irrigation suitability simulation. It took Macintyre Brook catchment as the study area, based on seven criteria layers and a landuse conversion restrict layer, which made the model more reasonable and effective. The analysis of this study mainly focused on highly suitable areas as these areas have highest

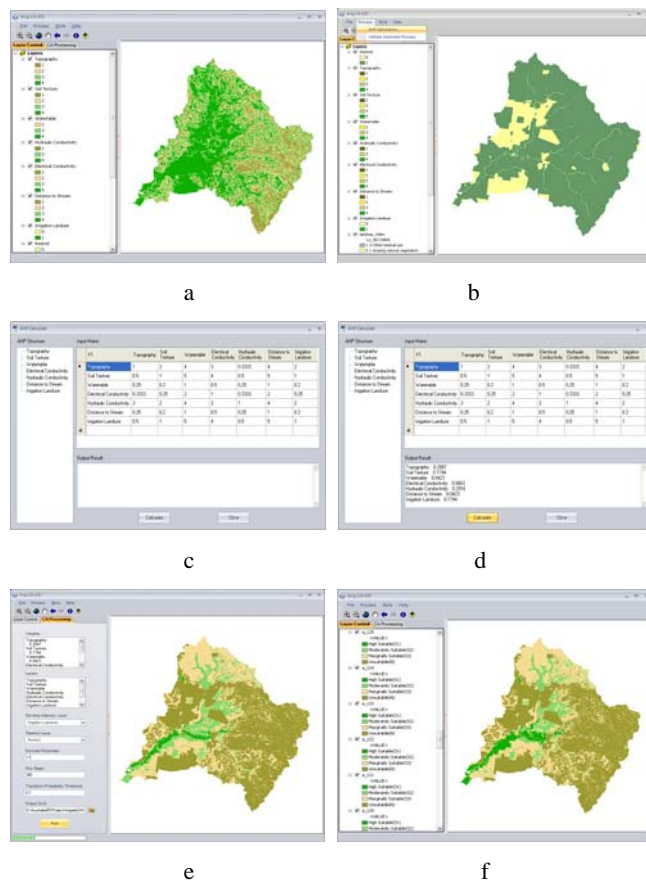


Figure 4. AHP-CA-GIS simulation tool interface.

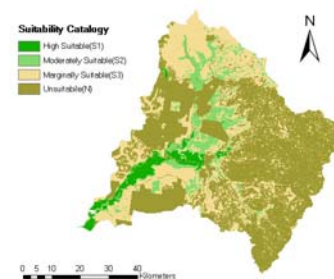


Figure 5. A selected suitability evaluation map of irrigated agriculture in Macintyre Brook Catchment.

potential for irrigated landuse. Through iteration and deduction of CA model and with some adjustments and rectifications, we generated a suitability map. The Paper also took into account interaction between geographical features. It deems that surrounding development degree will affect the related suitability of a site. It means that the regions alongside irrigated areas may have more chance to be developed. In addition, the current landuse types were analysed to deal with certain landuse which had little probability to be developed into agricultural land. These approaches made the result more in line with the actual decision-making requirements. The limitation of this study lies in the fact that, in the application of the model, there are still some uncertainties associated with the selection of two key parameters: discrete parameter and transform threshold. In combination with experts' participation and field investigation, special attention need to be paid to the determination of parameter values in future work.

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