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RAINWATER COLLECTION FACILITIES TO ALLEVIATE WATER DEFICIT IN KARST AREAS

***[1]Kwong Fai Andrew Lo, [1]Thomas Chao-Chun Huang and [2]Guanghui Jiang**

[1]Graduate Institute of Earth Science, College of Science, Chinese Culture University, Taipei 11114, Taiwan
[2]Key Laboratory of Karst dynamics, Institute of Karst Geology, Chinese Academy of Geological Sciences, Guilin 541004, P.R. China

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ABSTRACT

Karst areas are usually water deficit due to lack of surface runoff, groundwater exceeding 120 m depth, and no obvious sign of underground streams on the ground surface. Guangxi Province karst areas in the southwestern part of China are well known for its drought conditions. It is often classified as extremely fragile karst ecosystem. Rock desertification occurs easily in this region, due mainly to less soil cover, shortage in surface water resources, and difficult vegetation recovery. Although the water problem is temporally resolved with the discovery of underground streams using water cave investigations, water supply problems still exist in these areas owing to the large-scale human activities such as mining and water pollution hazard. This study uses the SWAT (Soil and Water Assessment Tools) model to assess the hydrologic environment in karst areas located in Yaji experimental site, Guilin City, Guangxi Province, China. Water runoff condition is estimated at the study site along with surface water yield and movement. Results are also utilized to establish rainwater harvesting management schemes, to enhance water resources supply efficiency, and to minimize soil loss and sediment yield. Optimum rainwater catchment sites may be selected at high water runoff and less soil erosion locations to harvest rainwater, to reduce soil and water related disaster risks, and to alleviate intensification of rock desertification problem.

INTRODUCTION

The forest cover in southwest China areas drops to less than 15%. The waterfalls in Huangguoshu in Guizhou has extended its annual dry season from two months in the 1980s to five months now and sometimes even dries up (Jiang et al., 2011). Rock desertification affects 80-90% of the forest land (3,000 km^2) in Mashan, Guizhou where forest coverage used to be 60-80%. More than 100,000 people's livelihood has been disrupted and has to be re-settled. Rock desertification has brought a loss of 2.8 billion yuan (US$338 million) to 77 counties in Guizhou. Of the 48 poverty-stricken counties, 39 are in rock desertification-stricken areas. There are more than three million poverty-stricken people and the poverty rate is ever increasing. Rock desertification also causes serious loss of soil and water, endangering the navigational safety in the Pearl and the Yangtze River (Yuan, 1993). About 270 million m^3 of sand is delivered to both Rivers, posing serious dangers to the electric power stations downstream also.

****Corresponding author: Kwong Fai Andrew Lo***
Graduate Institute of Earth Science, College of Science, Chinese Culture University, Taipei 11114, Taiwan.

Scientists have suggested that governments and scientific communities have to combine efforts to establish a comprehensive plan to control rock desertification using biological, engineering and management integrated approach. One attempt is to help peasants get rid of poverty and encourage them to give up crop farming and return to bamboo, grass or orchard farming, along with aforestation.

Karst areas are usually water deficit due to lack of surface runoff, groundwater exceeding 120 m depth, and no obvious sign of underground streams on the ground surface. The objective of this study is, therefore, to use the SWAT (Soil and Water Assessment Tools) model to assess the hydrologic environment in karst areas.

Water runoff condition is estimated along with surface water yield and movement. This information can be used to establish rainwater harvesting management schemes, to enhance water resources supply efficiency, to reduce soil and water related disaster risks, and to alleviate intensification of rock desertification problem.

MATERILS AND METHODS

Study Area

Yaji experimental site is chosen as the study area of this study. It is about 8 km east from Guilin City, Guangxi Zhuang Autonomous Region in South China. It is an experimental research site for karst study for decades since 1986 (Yuan et al., 1990). The site is located in the border region of Fenglin and Fengcong. Both of which are typical landform in Guilin and famous in the world (Sweeting, 1995). The total area of the experimental site is about 2 km^2. Elevation in the plain areas located in the eastern and western part is about 150 m. The highest peak in the study site is about 652 m whereas the valleys are within the 250 – 400 m elevation (Fig. 1).

The climate in Guilin is characterized as subtropical monsoon. It is hot and wet in summer, cool and moist in winter, with an annual temperature of 19.2^{o}C and an annual rainfall of 1,935 m. The precipitation in Guilin has two peaks. One of them occurs between winter and spring, when the sun move north and the wind from ocean become strong. It runs into the north continental wind of equal strength, leading to long rainfall periods. The other peak occurs in summer to autumn. It is often dry with short typhoon rainstorms.

The SWAT Model

The SWAT model is a physically based distributed model designed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds with varying soil, land use, and management conditions over long periods of time (Neitsch et al., 2011). SWAT subdivides a basin into sub-basins connected by a stream network and further delineates each sub-basin into hydrological response units (HRUs) consisting of unique combinations of land use and soils. SWAT allows a number of different physical processes to be simulated in a basin.

The hydrological routines within SWAT account for snowfall and melt, vadose zone processes (infiltration, evaporation, plant uptake, lateral flows, and percolation), and groundwater flows (Zhang et al., 2009). The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance.

The SWAT model simulates the hydrology into land and routing phases. In the land phase, the amount of water, sediment and other non-point loads are calculated from each HRU and summed up to the level of sub-basins. Each sub-basin controls and guides the loads towards the basin outlet. The routing phase defines the flow of water, sediment and other non-point sources of pollution through the channel network to an outlet of the basin. SWAT computes soil erosion at a HRU level using the modified Universal Soil Loss Equation (MUSLE). This process constitutes computing sediment yields from each sub-basin and routing the sediment yields to the basin outlet. The hydrological cycle simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{lat} - Q_{gw}) \quad \text{.... [1]}$$

where SW_t is the final soil water content, SW_0 is the initial soil water content on day i, t is the time (days), R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, w_{seep} is the amount of water entering the vadose zone from the soil profile on day i, Q_{lat} is the water percolation past bottom of soil profile in the watershed for day i, and Q_{gw} is the amount of return flow on day i. All water units are in mm H_2O. For more detail about SWAT theory, please reference SWAT2009 Theoretical Documentation (Neitsch et al., 2011) is available by downloading online (http://swat.tamu.edu/).

The Data Set

The basic datasets that are required by the SWAT hydrological model are topography, climate, stream flow, soil, and land use data (Table 1).

The current version, Arc-SWAT2012, was used to compile the SWAT input files. The experimental site is subdivided into small HRUs based on the digital elevation model (DEM) data, land use and soil type data, conforming to concentrated drainage pattern as well as similar hydrological responses. Based on just the DEM, land use, and soil data, the experimental site is further sub-divided into 89 sub-basins. The model ignores small basins as well as sub-basins that do not drain directly to the main basin along the boundary of the experimental site. As such, the study basin area is a bit smaller than the physical boundary of the experimental site.

The Arc-SWAT2012 is an ArcView extension. It provides a graphical user interface that allows for GIS data to be easily formatted for use in SWAT model simulations. ArcSWAT breaks preprocessing into four main steps: watershed delineation, HRU analysis, weather data definition and SWAT simulation. In order to understand how each section works within the modeling process, it is important to understand the conceptual framework of each step, as well as what data are used and how they integrate into ArcSWAT. Fig. 2 shows the flowchart of modeling using ArcSWAT.

RESULTS AND DISCUSSION

Hydrological Responses

The ArcSWAT model is used to simulate hydrological responses at the study site from 1979 to 2013 (Table 2). Table 2 also displays responses for individual year of 1993, 2003, and 2013. Results indicate that similar water and sediment yield for the year 1993 and 2013. Higher water and sediment yield in year 2013 most probably is due to the higher rainfall amount during that year. The overall average annual water yield between 1997 and 2013 is about 1,787 mm, whereas the average annual sediment yield is about 0.85 t/ha. The average annual runoff coefficient at the study site is about 39.21%.

Compared with previous water yield tracer studies conducted in the study site (Waltham, 2008), which is about 34%. Although the estimated value is a little higher, the difference is not that significant and it may have been caused by the higher annual rainfall used in the SWAT model.

Since the topography of Yaji experimental site consists of many small hills, elevation needs not be considered in site selection. Therefore, the runoff and sediment analyses provided by the SWAT model for each sub-basin should be adequate in determining the best locations to construct

Table 1. Spatial model input data for Yaji experimental site (Lo *et al.*, 2016)

Data type	Content	Resolution	Source
topography map	digital elevation model (DEM)	10 m	Institute of Karst Geology
land use map	land use classification	1:5,000	Institute of Karst Geology
soil map	soil type	1:50,000	Institute of Karst Geology
weather	precipitation, wind, relative humidity, and solar	daily	National Center for Environmental Prediction (NCEP) http://globalweather.tamu.edu/

Table 2. Annual hydrological responses for the year 1993, 2003, 2013 and the entire period 1979-2013 (Lo et al., 2016)

Year	PREC*	SURQ	LATQ	GWQ	LATE	SW	ET	PET	WATER YIELD	SED YIELD
1993	2153.10	10.76	1258.47	132.58	155.46	340.82	731.59	991.99	1410.25	0.22
2003	2147.15	35.51	1246.09	127.33	161.41	349.66	687.22	915.50	1416.83	0.21
2013	2737.35	37.93	1731.83	215.70	249.82	347.99	711.84	938.91	1997.35	0.53
1979-2013	2518.8	37.03	1552.74	187.58	217.32	342.22	711.4	938	1787.32	0.85

*PREC: Average amount of precipitation (mm), SURQ: Amount of surface runoff contribution from streamflow from HRU during simulation, LATQ: Lateral flow contribution to streamflow (mm), GWQ: Groundwater contribution to stream (mm), LATE: Water percolation past bottom of soil profile (mm), SW: Amount of water stored in soil profile (mm), ET: Actual evapotranspiration (mm), PET: Potential evapotranspiration (mm), WATER YIELD: Water yield to streamflow from HRUs (mm), and SED YIELD: Sediment yield from HRUs (t/ha).

Table 3. Different usage of runoff collection facilities

Facility type	Detention	Retention	Infiltration	Eco-environment sustainability	Water quality improve-ment	Recrea-tion
Dry pond	✓					
Wet pond	✓	✓		✓		
Wetland		✓	✓	✓	✓	✓
Bioretention storage		✓	✓	✓	✓	
Gravel-pore storage		✓	✓			
Rooftop rainwater catchment		✓				
Underground storage		✓				
Infiltration enhancement		✓	✓	✓	✓	✓

Fig. 1. Satellite (QuickBird) image of Yaji experimental site

This comparison also suggests that the SWAT model output is not too different from the actual field measurement.

Rainwater Harvesting Sites

The ideal siting for rainwater harvesting should satisfy the following design criteria: (1) upper reaches of the watershed; (2) maximum runoff interception; (3) minimum sediment load.

rainwater collection devices. To allow automatic site-selection, necessary design parameters such as the range of surface runoff (SURQ), water yield (WYL), and sediment yield (SED), need to be specified. For illustration purpose, for the year 1993, SURQ is set at >0.7205 mm; WYL at > 117 mm; and SED at < 2 t/ha. A total of 10 sub-basins are selected. Most are situated at the upper and lower eastern and western parts of the study site (Fig. 3).

The surface runoff pattern at these sites is characterized by high lateral runoff volume entering the collecting sub-basin, and thus, greatly inflated the total collected runoff volume. For the year 2003, SURQ is set at >2.793 mm; WYL at > 117 mm; and SED at < 2 t/ha.

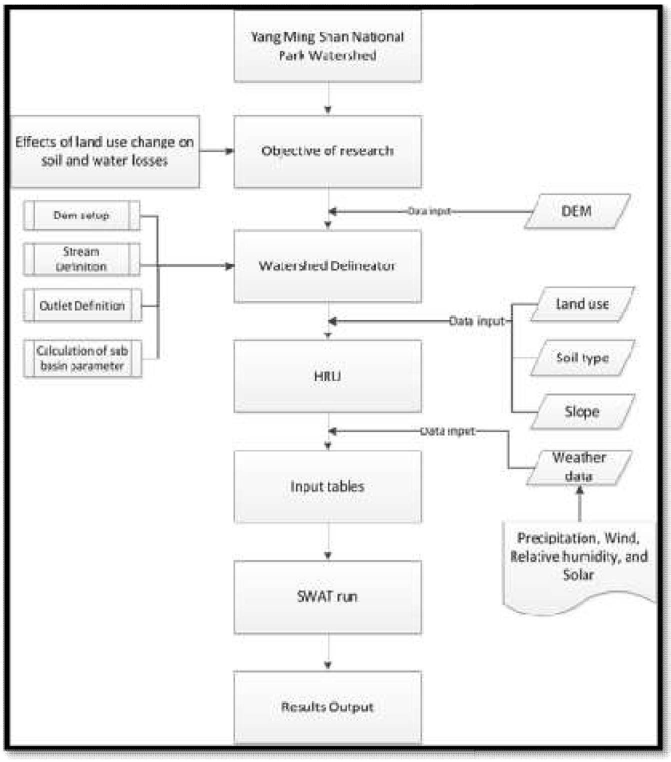

Fig. 2. Flowchart of ArcSWAT processing steps (Lo *et al.*, 2016)

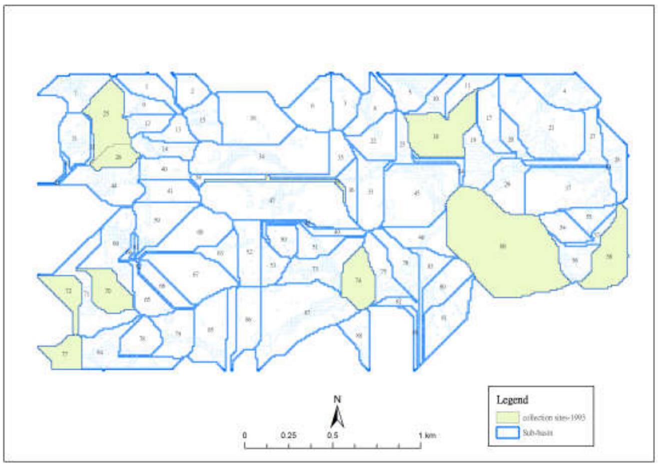

Fig. 3. Suitable rainwater collection sites for year 1993 (Lo et al., 2016)

A total of 10 sub-basins are also selected. Most are situated at the upper and lower western parts of the study site. For the year 2013, with a higher annual rainfall amount, SURQ is set at >2.9 mm; WYL at > 160 mm; and SED at < 2 t/ha. A total of 14 sub-basins are selected. Most are situated at the central and lower western as well as at the central eastern parts of the study site. Combining all three time periods (1993, 2003, 2013), the selected common sub-basins are located at three zones (Fig. 4):

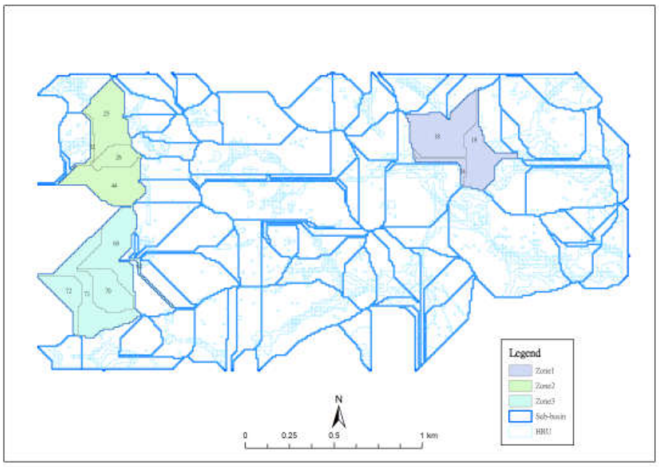

Fig. 4. Most suitable rainwater collection sites (Lo et al., 2016)

Fig. 5. Location of water tank near a village in karst areas, Fengshan, Guangxi

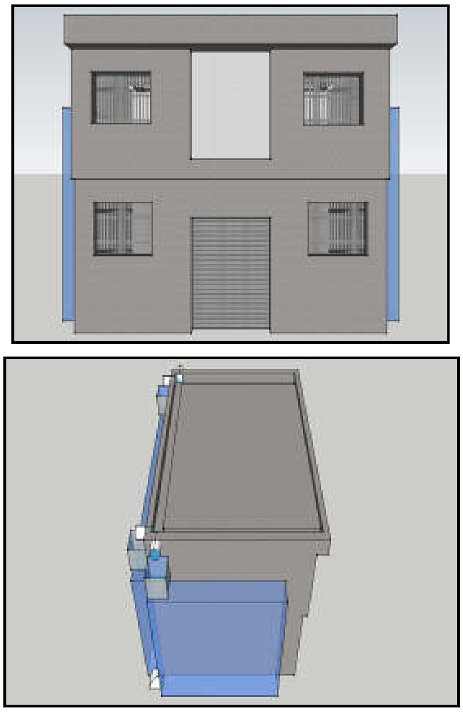

Fig. 6. A newly improved above ground rainwater harvesting scheme using the vertical walls of the residential house

Fig. 7. Schematic diagram of scattered low-impact runoff retardation facilities (Liaw et al., 2000)

Zone 1: sub-basin number 18, 19, 24
Zone 2: sub-basin number 25, 26, 32, 44
Zone 3: sub-basin number 62, 69, 70, 71, 72

These zones are concentrated at the western and northeastern parts of the study site. These sub-basins are most suitable for rainwater collection during both dry and wet years.

Runoff collection Facilities

There are many different types of runoff collection facilities. According to their usage, they can be classified as: (1) Dry pond (2) Wet pond (3) Wetland (4) Bio-retention storage (5) Gravel-pore storage (6) Rooftop rainwater catchment (7) Underground storage, and (8) Infiltration enhancement (Liaw and Tsai, 2002). Most runoff collection facilities may be used for storm detention, storm retention, infiltration, sustaining eco-environment, water quality improvement, and recreational purposes. Table 3 categorizes the different usage of these facilities. Various runoff collection facilities should be combined in actual implementation of rainwater harvesting. The selection should be able to adapt to different local conditions in order to achieve optimum effectiveness.

Rooftop Rainwater Catchment Systems

Rooftop of residential housing can be used to collect rainwater. The storage capacity is directly proportional to the construction area. It is very effective in densely paved urban cities. In USA, many state governments have included and implemented rainwater catchment in their building construction codes (Mileti, 1999). The collected rainwater may be stored underground or above ground. Water quality for underground storage is much preferred than above ground storage.
However, the high cost and construction hardship of building underground water tanks have discouraged wide spread adoption of underground tanks. The local people prefer to build their above ground water tanks in clusters around habitants in depressions (Fig. 5). It is at a higher position in the slope than houses and cultivated land in the bottom of depressions. Therefore, gravity can supply water for domestic use or irrigation. Rainwater is conveniently stored in unprotected open space. However, the quality is often degraded in dry periods and unfit for human consumption.

A better design, which is still in experimentation, is to make use of the vertical walls of the each residential house and constructs additional water-proof walls to store rainwater surrounding the house (Fig. 6). The protected closed vertical water storage tanks may provide convenient indoor water use and regulate extreme room temperature during hot summers and cold winters. This modified design may improve the cost and construction problems encountered in underground rainwater storage and increase the storage capacity significantly.

Other Runoff Collection Strategies

For adequate water supply in karst areas, using rooftop catchment systems may not be adequate since the dwelling land area comprises a tiny percentage of the total land area. Other runoff collection facilities may be used to achieve comprehensive water supply in the study area. The most appropriate solution is to construct many scattered dry ponds and wet ponds at the abandoned land use areas (Fig. 7).

Dry pond is extremely suitable for use in densely populated cities where land is very precious. Its regulative mechanism is restricted to a certain time period. It can store rainwater and runoff during heavy storms. After the rain stops, the collected rainwater and runoff may be drained out slowly. In addition to collecting runoff via temporary storage, it may also provide space for other purposes such as recreation parks, golf courses or parking lots (Lo and Liaw, 2002). Wet pond combines the existing and man-made ponds and lowlands. Both ponds and lowlands usually maintain low water flow, which may be able to collect runoff. They may provide stability to the aquatic ecologic system if continuous steady inflow and outflow is maintained. They are also beneficial for stabilizing the stream base flow and its ecologic environment. The open aquatic environment may contribute also to the aesthetic as well as water-friendly effects. As a recommendation to mitigate water shortage problems in karst areas, man-made retention ponds with 1 m depth and area ranging from 1,000 to 10,000 m^2 should be installed in aforementioned Zones 1, 2 and 3 in Fig. 4.

Conclusion

This study successfully verifies that the computer simulation SWAT model is capable of evaluating the hydrological responses in karst areas. It is also capable of identifying areas within the watershed with high runoff and erosion. This provides a useful guide for selecting the best sites to install rainwater harvesting systems.

The stored rainwater should be able to increase the availability of water resources, to reduce soil and water related disaster risks, and to alleviate intensification of rock desertification problem. However, to comprehensively mitigate water shortage problems in karst areas, other low-impact runoff collection technology such as dry ponds and wet ponds are also suggested to increase its storm water storage capacity. Treated rainwater may provide domestic drinking water need. Untreated rainwater may be used conveniently for non-potable uses such as irrigation, toilet flushing, landscaping, and groundwater recharge.

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