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ASSESSMENT OF RAINWATER COLLECTION SITES IN KARST AREAS USING THE SWAT MODEL

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

[1]Graduate Institute of Earth Science, College of Science, Chinese Culture University, Taipei 1114, 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

It is vital to study in greater detail the process of rainwater collection in epikarst zone, in order to enhance water storage, to accelerate water cycle and to improve water quality. This study focuses on assessing the hydrologic environment in the karst areas and also illustrates the use of computer modeling (SWAT Model) to select the best sites to install such rainwater collection devices. 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. The total area of the experimental site is about 2 km^2. The ArcSWAT model is used to simulate hydrological responses at the study site from 1979 to 2013 and for individual year of 1993, 2003, and 2013. Combining all three time periods (1993, 2003, 2013), the selected common sub-basins are located in three zones. 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. The stored rainwater should be able to increase the availability of water resources. Treated rainwater may provide domestic drinking water need. Untreated rainwater may be used for non-potable uses such as irrigation, toilet flushing, landscaping, and groundwater recharge.

INTRODUCTION

The geomorphology characteristic of karst areas in Southwest and South China forms well-developed underground river systems, intensive depressions and sinkholes. The ground surface is usually dry even though the annual precipitation is more than 1,000 mm. Groundwater extraction usually reaches 100 m depth and often fails if the subterranean stream location cannot be accurately determined. Water is often found in the aeration zone of the upper aquifer (epikarst) and is collected by water tank to meet the basic water supply requirements in rural households. Because epikarst zone needs to satisfy both ecological water consumption and evaporation, the water tank has small limited storage volume ranging from 50 to 500 m^3 and rather low water security. Severe droughts often occur after extreme weather events. In 2010, a severe drought happened resulting in drinking water shortage for more than 20 million people. Rainwater harvesting technology may be able to remedy the water shortage problem and may also enhance local economic development and ecological restoration.

Corresponding author: Kwong Fai Andrew Lo,
Graduate Institute of Earth Science, College of Science, Chinese Culture University, Taipei 1114, Taiwan.

According to the characteristic of karst landform and numerous international experience, rainwater harvesting should not only be restricted to roof collection and runoff from impervious surface, but should also include runoff from epikarst zone. Improvement on the water flow in the epikarst zone will increase both water quantity and quality. To enhance water storage, accelerate water cycle and improve water quality, it is necessary to study in greater detail the process of rainwater collection in epikarst zone. Most importantly the collected water should not only use for drinking, but also use for ecological restoration in degraded rock desertification environment. Therefore, this study focuses on assessing the hydrologic environment in the karst areas and also illustrates the use of computer modeling (SWAT Model) to select the best sites to install such rainwater collection devices.

THE 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.

MATEIALS AND METHODS

The SWAT (Soil and Water Assessment Tool) 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 hydrologic 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:

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

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 (Fig. 2). 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. Slope steepness and the land use map are shown in Figs. 3 and 4, respectively.

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. 5 shows the flowchart of modeling using ArcSWAT.

RESULTS AND DISCUSSION

Hydrological Responses

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

Selection of Collection Sites

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

Table 1. Spatial model input data for Yaji experimental site

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

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. Suitable sub-basins for rainwater collection (according to the following design criteria: [SED_1993] <2, [SURQ_1993] >0.7205, and [WYL_1993] >117)

Sub-basin	Area(ha)	SED_1993	SURQ_1993	LATQ_1993	WYL_1993
18	9.05	0.0049	0.7211	106.1210	117.447
25	6.93	0.0046	0.7230	105.8150	117.447
26	2.65	0.0047	0.7212	107.7240	118.104
39	1.02	0.0034	0.7223	105.4150	117.253
58	7.08	0.0044	0.7231	104.5960	117.003
68	28.08	0.0051	0.7225	104.7020	117.002
70	4.48	0.0053	0.7209	108.2520	118.234
72	3.33	1.6402	19.3790	31.0452	117.003
74	4.97	0.0047	0.7207	106.3050	117.496
77	3.20	0.0043	0.7233	105.5410	117.357

Table 4. Suitable sub-basins for rainwater collection (according to the following design criteria: [SED_2003] <2, [SURQ_2003] >2.793, and [WYL_2003] >117)

Sub-basin	Area(ha)	SED_2003	SURQ_2003	LATQ_2003	WYL_2003
25	6.93	0.0059	2.7932	105.0210	118.295
26	2.65	0.0058	2.7932	106.5240	118.362
31	4.58	0.0049	2.7934	102.6150	118.149
44	7.27	0.0040	2.7937	97.9713	117.834
62	0.34	0.0031	2.7936	99.8348	117.956
69	7.49	0.0028	2.7938	90.5649	117.363
70	4.48	0.0068	2.7932	106.9800	118.374
71	7.73	0.0038	2.7937	96.5734	117.742
72	3.33	1.2793	20.8031	30.8215	118.741
77	3.20	0.0054	2.7931	104.7960	118.275

Table 5. Suitable sub-basins for rainwater collection (according to the following design criteria: [SED_2013] <2, [SURQ_2013] >2.9, and [WYL_2013] >160)

Sub-basin	Area(ha)	SED_2013	SURQ_2013	LATQ2013	WYL_2013
19	5.87	0.008	2.910	92.806	165.041
24	0.98	0.006	2.910	92.589	165.047
30	0.03	0.001	2.925	13.111	164.345
32	0.63	0.040	20.031	57.904	161.140
42	0.29	0.002	20.097	1.238	160.776
43	0.40	0.004	20.090	2.657	160.784
44	7.27	0.010	2.903	135.661	166.284
61	0.28	0.003	2.924	66.263	164.901
62	0.34	0.008	2.902	138.315	166.385
64	0.500	0.003	2.928	42.379	164.677
69	7.490	0.007	2.908	125.251	165.916
71	7.730	0.010	2.904	133.685	166.205
82	1.440	0.007	2.909	92.794	165.010
89	0.920	0.006	2.911	92.367	165.043

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

Fig. 2. Distribution of sub-basins and HRUs at Yaji experimental site

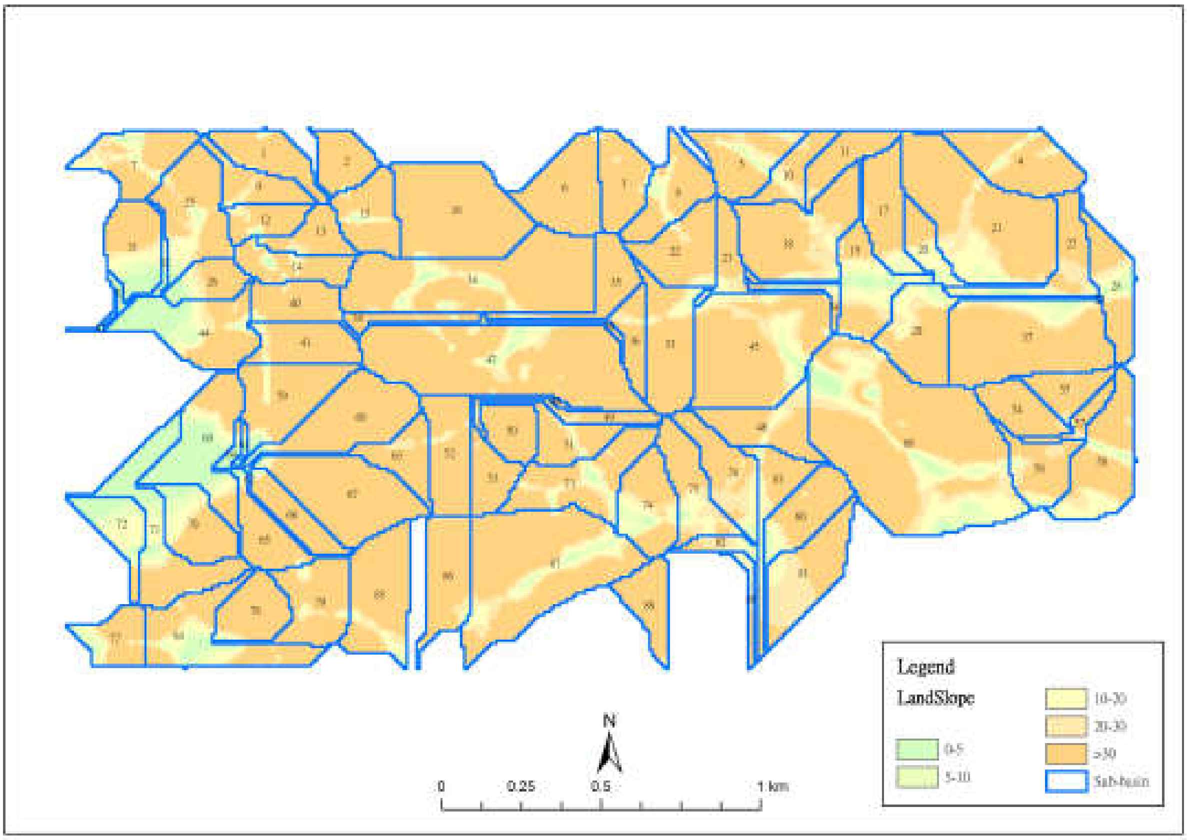

Fig. 3. Slope steepness map of Yaji experimental site

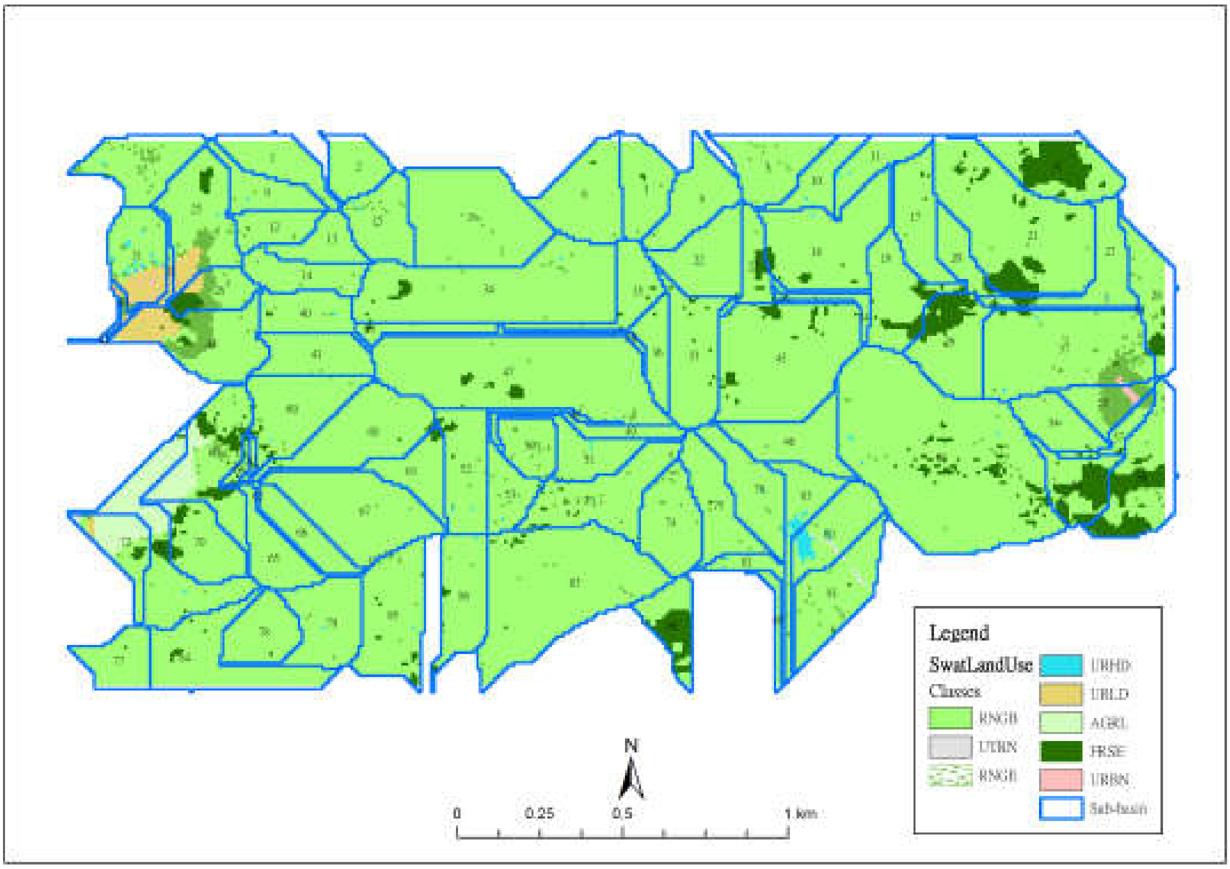

Fig. 4. Land use map of Yaji experimental site (RNGB: shrub land, UTRN: road, RNGE: grassland, URHD: bare rock, URLD: bare land, AGRL: farmland, FRSE: forest, URBN: constructed land)

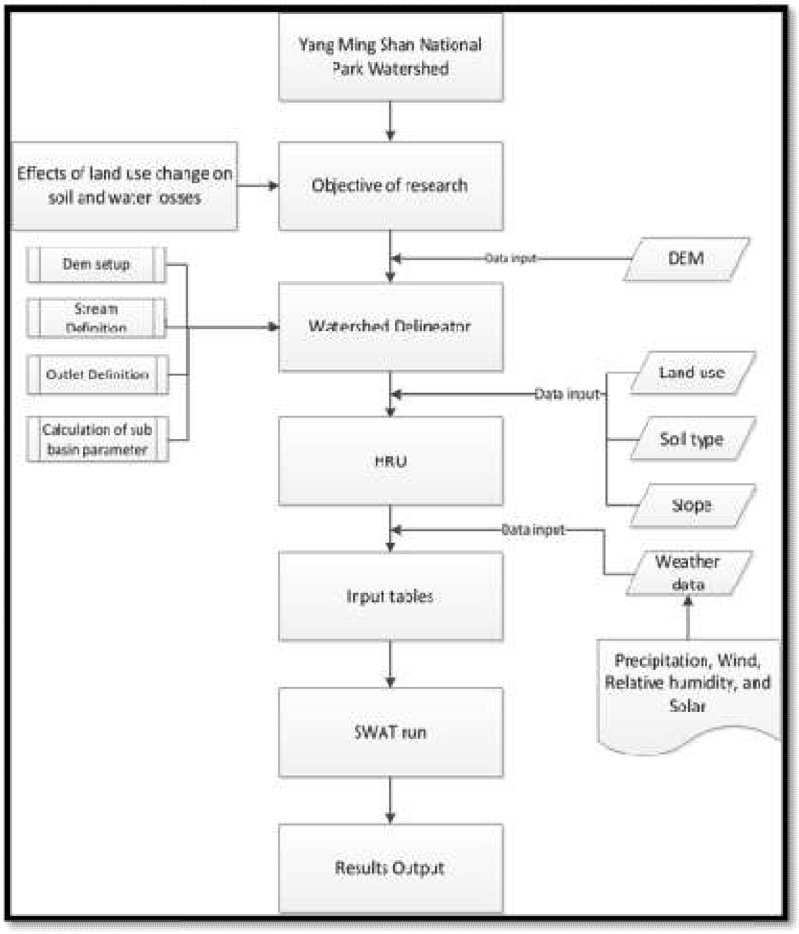

Fig. 5. Flowchart of ArcSWAT processing steps

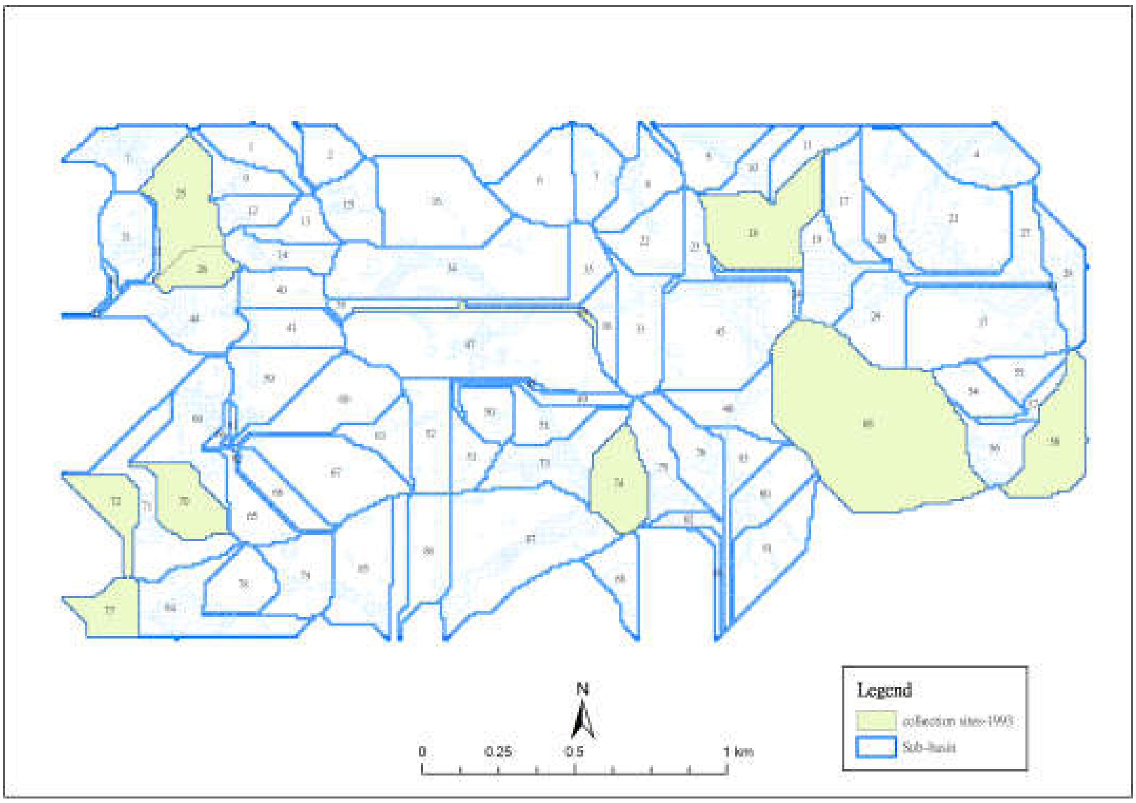

Fig. 6. Suitable rainwater collection sites for year 1993

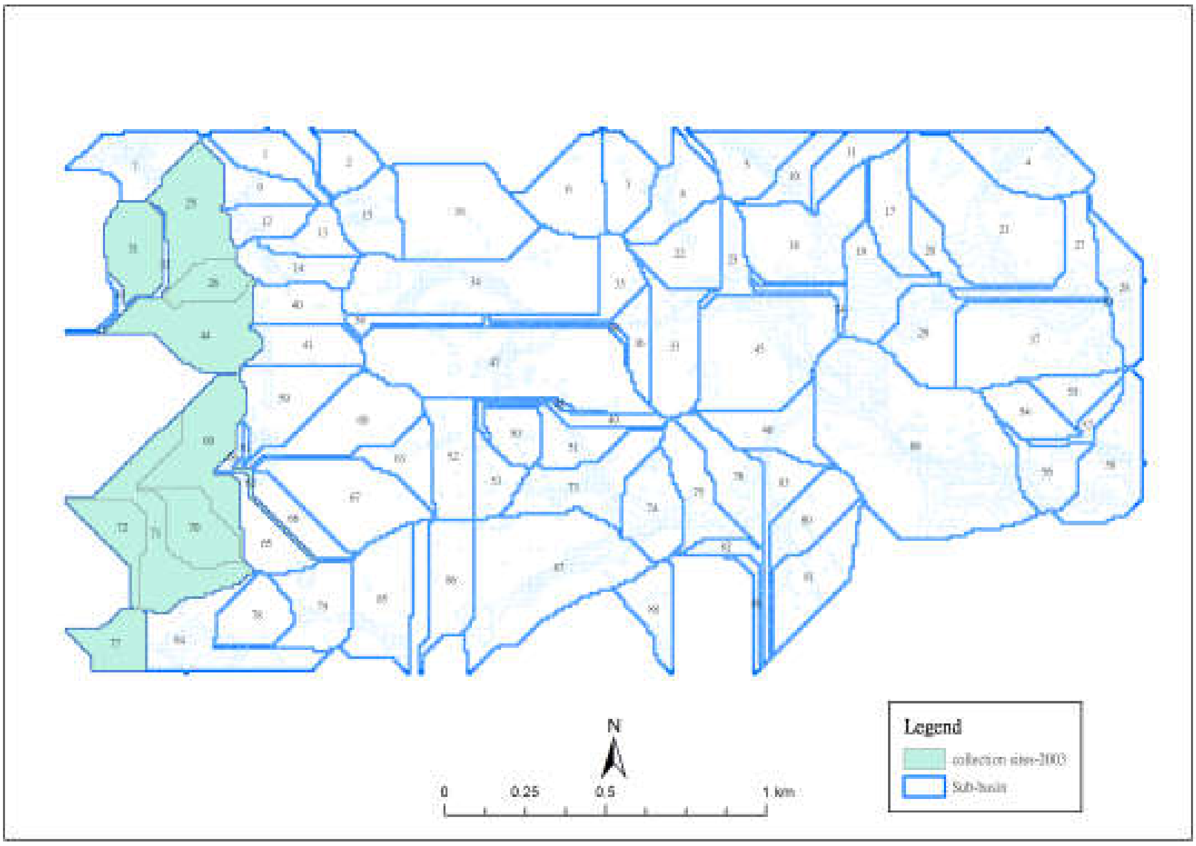

Fig. 7. Suitable rainwater collection sites for year 2003

Fig. 8. Suitable rainwater collection sites for year 2013

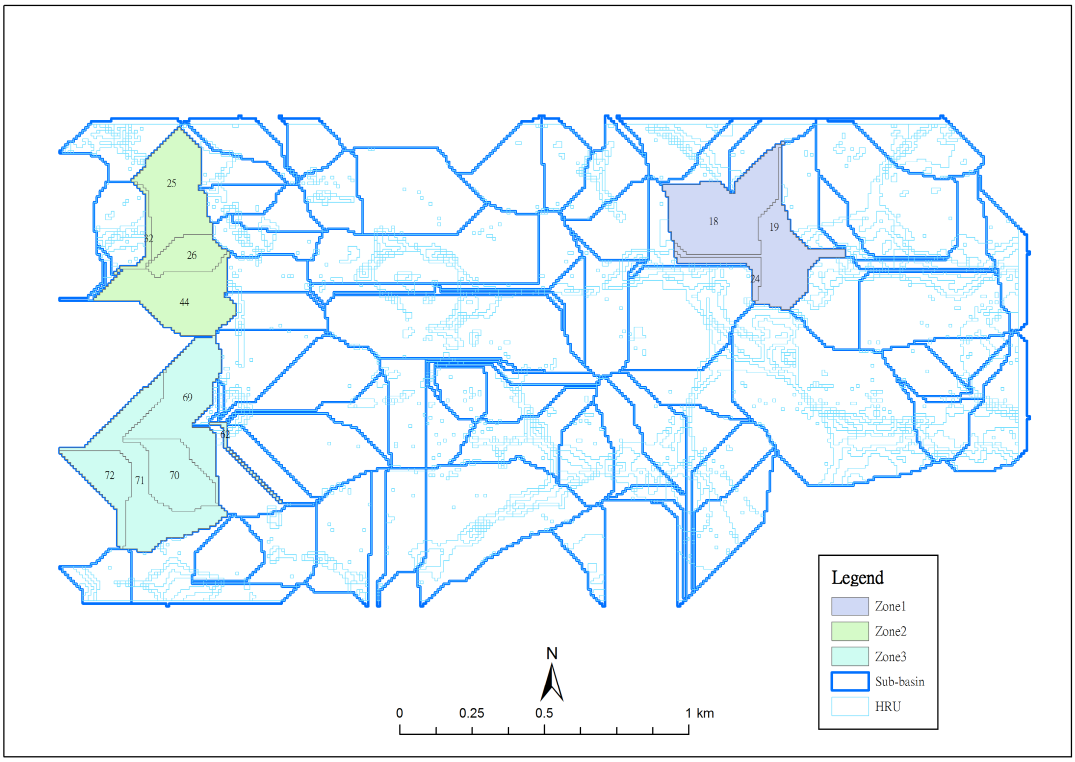

Fig. 9. Most suitable rainwater collection sites

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 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 (Table 3). Most are situated at the upper and lower eastern and western parts of the study site (Fig. 6). 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. A total of 10 sub-basins are also selected (Table 4). Most are situated at the upper and lower western parts of the study site (Fig. 7). 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 (Table 5). Most are situated at the central and lower western as well as at the central eastern parts of the study site (Fig. 8). Combining all three time periods (1993, 2003, 2013), the selected common sub-basins are located at three zones (Fig. 9):

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.

Conclusion

The SWAT model is a computer simulation model capable of evaluating nonpoint source pollution at any point within a watershed. It is also capable of identifying areas within the watershed with high runoff and erosion. This provides a guide useful for selecting the best sites to install rainwater collection devices.

The stored rainwater should be able to increase the availability of water resources. Treated rainwater may provide domestic drinking water need. Untreated rainwater may be used for non-potable uses such as irrigation, toilet flushing, landscaping, and groundwater recharge.

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