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EFFECTS OF CLIMATE CHANGE ON URBAN RAINWATER HARVESTING IN TAIPEI CITY, TAIWAN

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ABSTRACT

Cities are becoming increasingly vulnerable to water related issues due to rapid urbanization, installation of complex infrastructure, and changes in the rainfall patterns. This study aims at assessing the impacts of climate change on rainwater harvesting systems (RWH) at the tropical urban city Taipei, Taiwan. The future climate change projections are downscaled from global circulation models to urban catchment scale using the Long Ashton Research Station Weather Generator (LARS-WG) of the Intergovernmental panel on Climate Change (IPCC), Fourth Assessment Report (AR4) - coupled with inter comparison project (CMIP3) model results. Historical rainfall data from 1981- 2010 is used to simulate long-term future rainfall data from 2011-2099. The percentage change of the rainfall is calculated. The rainfall patterns are analysed based on the daily, monthly, seasonal and annual time scales. Water requirements are calculated based on the selected scenario types. Rainfall and water demand data are incorporated into a water balance model. Climate change impacts for the selected RWH scenarios are calculated based on the water security analysis for each scenario. Analysis of the future rainfall data of Taipei reveals that there will be more extreme rainfall and rainfall events than before. Most of the selected global circulation models in this study predict that there will be more rainfall towards the end of this century (2080-2099). However, according to the A1B emission scenario, the long-term overall annual rainfall of Taipei shows a decreasing trend within this century. Residential RWH systems will be more affected than non-residential systems. RWH systems in Taipei should include potential future climate changes in their future design and planning and be prepared for excess runoff and additional measures against potential overflow and urban floods.

INTRODUCTION

Evidence of global warming in response to rising atmospheric levels of carbon dioxide and other greenhouse gases are accumulating (Kerr, 1990). Based on Atmospheric Ocean-coupled Global Circulation Models (AOGCMs), it has been suggested that a doubling of ambient carbon dioxide (CO_2) concentrations could increase the global mean air temperature by 1.4-5.8 °C from the pre-industrial level (Houghton *et al.*, 2001). Climate change and global warming will result in increased temperatures and strongly affecting many aspects of hydrological systems, water resources, coastal zones and oceans (Rosenzweig *et al.,* 2007). Rainwater harvesting (RWH) has been practiced for many purposes in different manners in many parts of the world for centuries. Rainwater harvesting has been widely accepted around the world as one of the main alternative source of water (Ghisi *et al.*, 2006; Helmreich and Horn, 2009; Herrmann and Hasse, 1997; Zhang *et al.*, 2009) and also it is considered as one of the best practice in combating urban floods. RWH has been practiced for many years in Taiwan. Taiwan is a good candidate for practising RWH due to the fact that Taiwan receives abundant rainfall throughout the year (Cheng and Liao, 2009). In the recent past, RWH is commonly used in the urban context as well as in the rural areas. With the increased trend in the urban green buildings, RWH has become a mandatory requirement of modern buildings (Cheng *et al.*, 2003).

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It is evident that there will be more RWH systems added to the total existing number in the near future. Possible climate changes in Taipei will affect the existing and future RWH systems. However, little is known about the effects of the climate change over RWH practices in the Asian region. Though there has been some studies carried out elsewhere in the world. Case studies from the existing RWH systems in Taipei have shown that there are significant economic savings as well as environmental benefits (Lo, 2005). Any effects of these systems therefore will have an impact on the practitioner's economy and the local environment. Results obtained from the AOGCM are considered as the most reliable climate change projections in the world as this work involved many of the most world-renowned academic and research institutions. Despite the significant increase in computational power in recent years, climate models still remain relatively coarse in space and time resolution and are unable to resolve significant features at finer scales of urban drainage systems. The coarse scale and bias in the rainfall results of climate models require some sort of downscaling techniques.

Dynamic downscaling techniques based on physical/ dynamical links between the climates at large and at small scales, and statistical downscaling methods using empirical relationships between large-scale atmospheric variables and observed daily local weather variables, are the two main techniques used. Statistical downscaling (SD) technique is a method used to derive local-scale information from larger scale through inference from the cross scale relationship using some random and/or deterministic functions (Salathé, 2003).

One method of using the statistical downscaling is through stochastic rainfall modelling. The model can be used with the parameters that have probability distributions, conditionally based on the coarse scale climatic predictor. The parameters of the stochastic model are obtained from statistical analysis of time series, and can be altered in accordance with climate model simulation results. This study uses the LARS-WG model as the main weather generator model for predicting the future rainfall. The LARS-WG model have been successfully applied in many similar case studies (Hashmi *et al.,* 2009; Hassan, 2012; Semenov and Barrow, 2002; Semenov and Stratonovitch, 2010). LARS-WG model itself consists of 15 different AOGCM model results according to different emission scenarios. However, this study utilizes only six selected AOGCMs for performing the analysis (Table 1). The main objective of this paper is to review and compares the climate change impacts on the RWH systems in Taipei City, Taiwan. This study hypothesis there is an effect from the potential climate change scenarios on the RWH systems in Taipei City. This study also identifies the past changes in the rainfall regimes of Taipei and performs a detailed analysis of LARS-WG by downscaling the global circulation models projections, as well as a comparison of past data with projected future rainfall data. Finally, with an overview of the possible future changes in the rainfall, the effects of the rainfall change on the RWH systems in Taipei City are identified with possible future climate change.

MATERIALS AND METHODS

Study Area

Taiwan is an island located at the west edge of the pacific between Japan and Philippines (Fig. 1). This tobacco leaf shaped island has an approximate land area of 36,000 km^2. Two-thirds of the entire island is mountainous. Taiwan's land use is mainly forest, about 58.37% of the total area; followed by agricultural land, about 22.94% of the total area; the rest is made up of urban buildings, transportation, water works facilities and other uses (EPA, 2011). Taiwan is located in the effective area of the subtropical monsoon zone, on the north-western Pacific Ocean and has an abundant supply of rainwater (average annual rainfall about 2,500 mm). Taiwan is also under the effect of typhoon and frontal storm activities. On the average, there are about 3 to 4 typhoons annually in Taiwan, mostly in July to September period (CWB, 2013). Taipei City has an annual rainfall of 2,405 mm (1981 - 2010) and the minimum and maximum temperatures of 20.4 ^{o}C and 26.6 ^{o}C, respectively.

Table 1. Some selected Atmosphere Ocean-coupled Global Climate Models (AOGCMs) available for the LARS-WG model

Model Name	Available SRES Scenarios	Agency
CM2.1 - AOGCM - GFDL- (GFCM21)	A1B / A2 / B1	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory (USA)
UKMO-HadCM3 (HADCM3)	A1B / A2 / B1	Hadley Centre for Climate Prediction and Research / Met Office (UK)
INM-CM3.0 (INCM3)	A1B / A2 / B1	Institute of Numerical Mathematics, Russian Academy of Science, Russia.
IPSL-CM4 (IPCM4)	A1B / A2 / B1	Institut Pierre Simon Laplace (France)
MPI_ECHAM5 (MPEH5)	A1B / A2 / B1	Max Planck Institute for Meteorology (Germany)
Community Climate System Model, version 3.0 (CCSM3 / NCCCSM)	A1B / A2 / B1	National Center for Atmospheric Research (NCAR), (USA)

Geography of Taiwan is characterized by high, steep mountains and it is difficult to store rainwater without reservoirs (Tsai and Huang, 2011). There are three main sources of water in Taiwan: reservoir water (24%), river water diversions (56%), and groundwater pumping (20%). Xindian River is the main source of potable water in Taipei City. To prevent ground subsidence and associated damages due to excessive groundwater extraction, the government has banned groundwater use in the Taipei Basin in the early 1970s. The groundwater table has stabilized since the late 90s (Chen *et al.,* 2007). Taipei City is surrounded by hills. About 47.81% of the total city area has been developed. Construction occupies the largest land area (26.18%). As of the end of 2012, each resident is able to enjoy an average of 51.63 m^2 of the green space and an average of 5.11 m^2 of park area. More than 80% of the urban households are living in apartments. Most residents (48.47%) live in buildings with 4 - 6 stories and only 12.34% live in single family houses (TCSY, 2013).

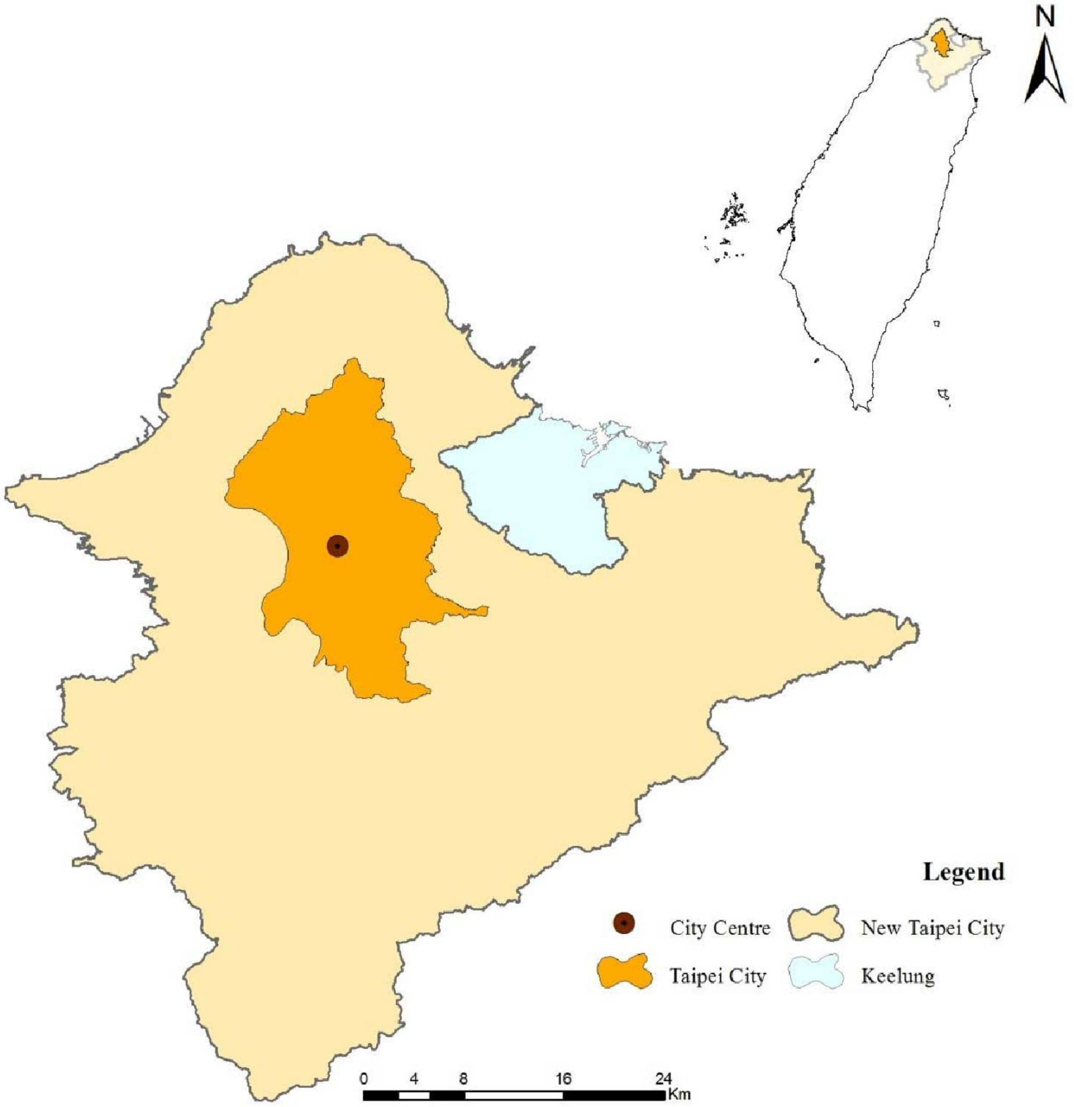

Fig. 1. Location map of Taipei City, New Taipei City and Keelung City, Taiwan

Data

Historical daily rainfall data (1981 to 2010) of Taipei City are obtained free of charge from the Central Weather Bureau. The future climate data used in this work are obtained from the statistical downscaling using the LARS-WG Model. Other data related to the water usage and demographics are obtained from the Department of Census and Statistics.

Statistical Downscaling of Climate Change Projections

Semenov and Barrow developed the Long Ashton Research Station Weather Generator (LARS-WG) in 1997. This stochastic model was capable of simulating future local climate variation in response to climate change by downscaling AOGCMs outputs. Version 5.5 of LARS-WG is used. Historical datasets, as input, is capable of simulating a daily weather time-series of infinite lengths. Three steps are performed in the LARS-WG model to develop the synthetic weather data. The model first calibrates and validates the past 30 years of historical daily rainfall data at Taipei City, using the 'site analysis' (Step 01) and 'Q Test' (Step 02) options. The 'generator' (Step 03) option generates synthetic weather data of one hundred years of future daily rainfall data. The generated future weather data are used in the site analysis step to obtain the basic statistics for the comparison. The LARS-WG is a site specific and model specific tool. Thus, this procedure is repeated for each selected site as well as for each selected climate model. These steps are further explained by Semenov and Barrow (2002) and Semenov and Stratonovitch (2010) with examples.

The LARS-WG model integrates 15 climate models from the multi-model ensemble used in the IPCC Fourth Assessment Report (AR4) to reduce uncertainty in climate predictions resulting from structural differences in the global climate models as well as uncertainty due to variations in initial conditions or model parameterizations (Semenov and Stratonovitch, 2010). However, LARS-WG model is still in development phase and not stable at all times. Uncertainties in climate change projections increase with the length of the time horizon. In the near-term (the 2020s), climate model uncertainties play the most important role; while over longer time horizons, uncertainties due to the selection of emissions scenario become increasingly significant (Jenkins and Lowe, 2003). Evaluating global/regional impacts from possible climate change on urban drainage requires a methodology to estimate extreme and short-duration rainfall statistics for the time period and the geographical region of interest. The generation of daily series of future climate projections for each selected model output is based on the SRES (Special Range of Emissions Scenarios) A1B emission scenario. This scenario represents an average future condition. Therefore, any climate projection under this emission scenario will have a better representative value for the future. This study has opted to involve the other two extreme emission scenario cases, A2 and the B1 only in the annual rainfall evaluation phase and used the A1B emission scenario results for the future analysis.

Climate Change Detection

Projected future rainfall data are studied, as it is the most important climatological variable in hydrologic modelling of RWH systems. Statistical comparison of the simulated rainfall values with their equivalent historical values are carried out to detect possible changes, both qualitatively and quantitatively. One-way analysis of variance (ANOVA) is used to assess whether there is any difference between the models projected rainfall data. Each model output daily rainfall series is compared with t-test (unequal or equal sample sizes, unequal variances / Welch's t-test) to check whether there is any statistically significant difference between the projected daily rainfall and the historical baseline data. The average projected rainfall values are compared with each AOGCM model. The model projections are analysed for percentage change compared to baseline values to identify changes using equation (1). A positive value indicates an increase and a negative value indicates a decrease in total rainfall. A zero percentage change indicates no change between future and observed parameters.

$$\textbf{Percentage Change} = \frac{(\boldsymbol{Projected} - \boldsymbol{Observed})}{\boldsymbol{Observed}} \times \mathbf{100}\% \quad (\mathbf{1})$$

Rainwater Harvesting System Modelling

The basic water balance model is utilized in determining the hydrological parameters of the RWH system. Hypothetical cases of average RWH systems and average households are used for the system calculations. The system values for each case type are chosen to represent the real world systems in Taipei City. This study calculates the water demand for both outdoor and indoor, small to large average households, and the potential runoff from the catchments.

These values are then applied to the water balance model and subsequent water security analysis. Total indoor non-potable water consumption and the total outdoor water consumption are calculated in m^3 and sum of these two demands is considered as the total monthly non-potable water demand for the RWH system. Household scenarios consider average urban households, whereas non-residential scenarios are referred to urban office or a commercial building with non-resident workers. Non-potable water consumption is considered in households. The water consumption rates are based mainly on toilet flushing, car washing and other uses (Table 2).

Landscape evapotranspiration from the outdoor landscapes accounts for the major outdoor water demand. Equation (2) is used to estimate its value.

$$\mathrm{ET}_{\mathrm{L}} = \mathrm{K}_{\mathrm{L}} \times \mathrm{ET}_{\mathrm{o}} \quad (2)$$

ET_L = landscape evapotranspiration, K_L= landscape coefficient, ET_o = reference evapotranspiration

Reference evapotranspiration (ETo) is estimated from a class A evaporation pan. ETo values are collected from the weather station assigned to the study site (CWB, 2011). This study uses the average monthly ET_o values at Taipei City. Landscape coefficients (K_L) are calculated using the following three factors: species (KS), density (Kd), and microclimate (Kmc). Since the study site is at Taipei City, an urban setting with lots of absorbing and reflective surfaces, the microclimate factor Kmc is assumed “high” value (0.8), species factor KS of “moderate” factor value (1.0) and “average” density factor Kd value (1.0). Landscape evapotranspiration values obtained from equation (2) are used to calculate the total monthly outdoor water requirement, based on the average irrigated land area (Table 2).

$$\mathrm{Q}_{\mathrm{out}} = \mathrm{ET}_{\mathrm{L}} \times \mathrm{A} \times \mathrm{D} \quad (3)$$

Q_{out} = monthly outdoor demand (m^3), ET_L = average landscape evapotranspiration (m),
A = irrigated land area (m^2), D = days for the month

It is assumed that the total monthly non-potable water demand is first fulfilled by the RWH system. The generated runoff from the RWH system catchment is diverted to the storage tank. The available storage capacity is compared with the accumulated runoff. If the accumulated runoff is greater than the available storage volume, excess water will be deducted from the accumulated runoff and will be released as excess water. Total water demand is deducted from the accumulated / harvested rainwater.

Table 2. Hypothetical scenario types of the RWH systems at Taipei City

Scenario Type	Water use	Water use rate (l/day)	Average number of people in concern	Catchment area category	Average catchment area size (m^2)	Average size of the rainwater storage tank (m^3)	Potential irrigated Area (m^2)
Residential – Type A	Low	150	4	Small	200	50	2
Residential – Type B	High	300	4	Small	200	50	2
Non Residential - Type A	Low	20	50	Medium	2000	200	10
Non Residential - Type B	High	40	50	Medium	2000	200	10
Non Residential large scale (indoor) - Type C	Medium	30	1500	Large	25000	1000	500
Non Residential large scale (outdoor) - Type D	Medium	30	500	Large	25000	1000	25000

If the total water demand is greater than the harvested rainwater in the tank, model assumes that the remaining water demand is met by the public water supply or other source. A monthly water balance model, equation (4), is set up using the Microsoft Excel software to compute the average volume of rainwater used each month and the average volume left behind in the tank at the end of the month.

$$Q_{\text{tank t1}} = Q_{\text{tank t0}} + Q_{\text{in}} - Q_{\text{out}} \qquad (4)$$

$Q_{\text{tank t1}}$ = water stored at any month, $Q_{\text{tank t0}}$ = water remained in the tank from the previous month,
Q_{in} = monthly harvested rainwater volume, Q_{out} = monthly gross non-potable water requirement

Above computational procedure is repeated with different system variables for the given scenario types (Table 2). Performances of the designed RWH systems are compared with the present and future scenarios.

Water Security

The ratio of water demand to water supply represents water stress resulting from an imbalance between water use and water resources (World Resources Institute, 2003). This study uses the “water security” as the key index to determine the climate change impact on the RWH systems. Water security can be defined as the percentage of the household water demand fulfilled by the RWH system. This allows calculation of the amount of water used and the amount of rainwater utilized, under a given daily rainfall time series, when water demand and roof area are known.

$$\mathbf{WS} = \frac{\sum \mathbf{Q_{abs}}}{\sum \mathbf{Q_{req}}} \times \mathbf{100} \qquad (5)$$

WS = water security (%), Q_{abs} = withdrawn volume of water from the tank,
Q_{req} = total volume of the household water requirement.

This study analyses the water securities with projected future rainfall values from the model output and to detect the potential future changes in the water security of the standard RWH systems for each scenario type (Table 2). Change in the water securities with respect to the different RWH scenario types are calculated in order to get a closer look at the impacts using water security values of the historical and projected averages, and based on equation (1).

RESULTS AND DISCUSSION

Weather Data Analysis

This study utilizes past 30 years of daily rainfall data which is the minimum requirements for most climate related studies and selects the weather station in the centre of the Taipei City. Average annual rainfall for Taipei City is 2,405 mm. The long-term trend of this annual rainfall records shows that there is a slight increment with some record high rainfall values occurring in the recent past (Fig. 2). Historical records show that Taipei City receives adequate amount of rainfall for many water sources to thrive, including RWH system to perform well. However, there are more dry days than wet days in Taipei City, marking the importance of additional water supplies such as RWH. It is also interesting to note the large standard deviation (about 602 mm) of the annual rainfall (Table 3).

Table 3. Basic descriptive statistic data for the annual rainfall data at Taipei study site (1981 – 2010)

Parameters	Values
Time period (years)	30
Mean (mm)	2405.12
Median (mm)	2289.15
Maximum (mm)	4404.70
Minimum (mm)	1192.50
Standard deviation	601.99
Average annual wet days	165.51
Average annual dry days	199.74
Wet/Total ratio	0.45
Dry/Total ratio	0.55

This further emphases the importance of RWH systems as supportive water source during dry periods. Taipei City experiences a subtropical climate, heavily influenced by the ocean and the movement of airflows controlling the East Asian monsoon. Most of the rain falls in two monsoon seasons, one between October and March and a second between May and June. In fact, the large standard deviations also coincide with these periods.

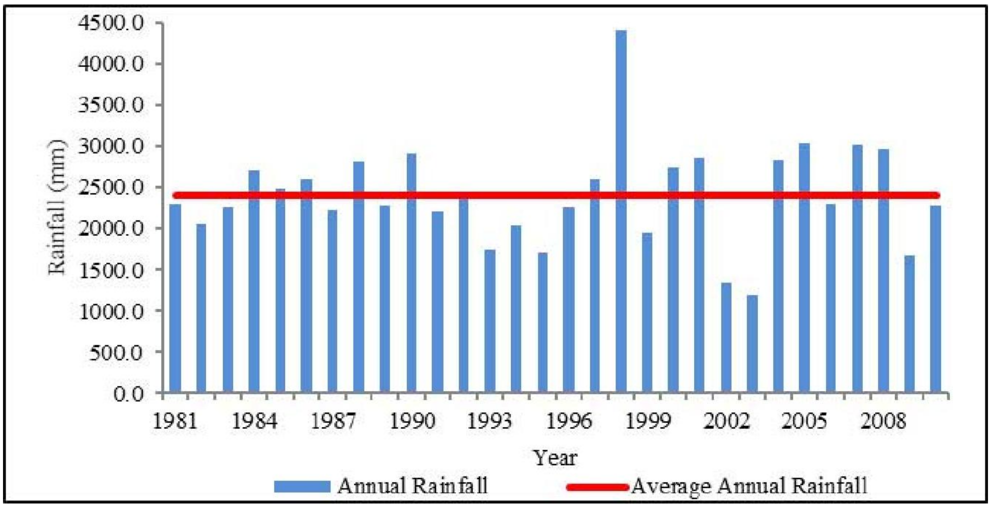

Fig. 2. Average annual rainfall in Taipei City area (1981-2010)

Taipei's climate is prone to extreme weather events, particularly in the summer when storms sweep in from the Pacific. On the average, three or four of these storms, known as typhoons, reach Taiwan's shores each year. Most arrive in the period between July and October and originate around the Caroline Islands and the Philippines, according to Taiwan's Central Weather Bureau. The typhoons bring extremely wet and windy weather and can cause tremendous damage, including the destruction of crops, flooding and landslides, and can lead to outbreaks of waterborne diseases like cholera. Global climate change seems to be affecting Taipei's climate. Government figures suggest that temperatures in Taipei have risen by 1.4 ^{o}C over the last 100 years, twice the rate of rise experienced worldwide. Higher average temperatures around Taipei are likely to alter weather patterns and annual precipitation, which would have a serious impact on the agricultural sector.

In summer months, there are usually convective afternoon thunderstorms in Taipei due to higher seasonal temperatures. These climatological phenomena may have influence on higher rainfall amount and will result in excessive runoff, sometimes even leading to flash flood occurrences. In general, RWH systems are not designed to capture all of the rainfall, which is also not practical. However, RWH systems in Taipei need to consider the fact that, following these high rainfall periods there is a relatively long dry period. Therefore, a sufficient amount of water from the high rainfall should be captured by the RWH system to be utilized in the dry period. Excess rainfall captured by RWH systems during the wet periods may be able to alleviate flash flood incidents also. Fig. 3 shows the cumulative probability distribution of historical daily rainfall distribution in Taipei from 1981-2010. The rainfall distribution follows a power law function; whereas the extreme daily rainfall records (the outliners) follow a linear pattern. There have been 9 very extreme rainfall events in Taipei. The maximum daily rainfall exceeds 854 mm and lasts for 4 days. Therefore, Taipei RWH systems will have to be aware of this potential extreme risk in their future planning.

Statistical Downscaling of Climate Change Projections

It is more effective to use different type of AOGCMs and emission scenarios in determining the future climate change. This helps to identify a wide spectrum of the different climate change projections and allow possible comparison between different emission scenarios. Although most AOGCM outputs are available for all three emission scenarios, this study selects only six AOGCM model results. The cumulative probability distribution of the projected daily rainfall series is given in Fig. 4. These model projections are for one hundred years, whereas the historical data set is given for thirty years. In general most of the model projections managed to project the future rainfall with a similar pattern than that of the historical data set as given in Fig. 3. However, as shown in the figure, there is some variability between the model projections. There seems to be more odd events or extreme events of the projected data series than compared to historical records. Apart from the INCM3 model results, the rest of the model results behave rather similarly (Fig. 4). Fig. 5 shows the percentage change of mean daily rainfall.

According to Fig. 5, February, May and October months report to have all model projections with positive change, whereas month of October shows a clearly higher rainfall projection compared to other months. June and December months report having all model projections with negative rainfall changes, while other months have mixed projections. Fig. 6 shows percentage change of maximum daily rainfall. The majority of the positive changes are reported in the last six months, while the majority of the negative maximum rainfall changes are reported in the first few months. This trend signals the use of RWH can be useful, especially during the first few months of the year. However, to effectively utilize the harvested rainwater, the system should be capable of capturing enough rainfall from the rainy days of the later months of the year. Monthly rainfall variations with the selected climate change projections for the scenario A1B are given in Fig. 7. In general, the projected monthly rainfall shows small variations than that of the historical mean value for all six selected climate change models.

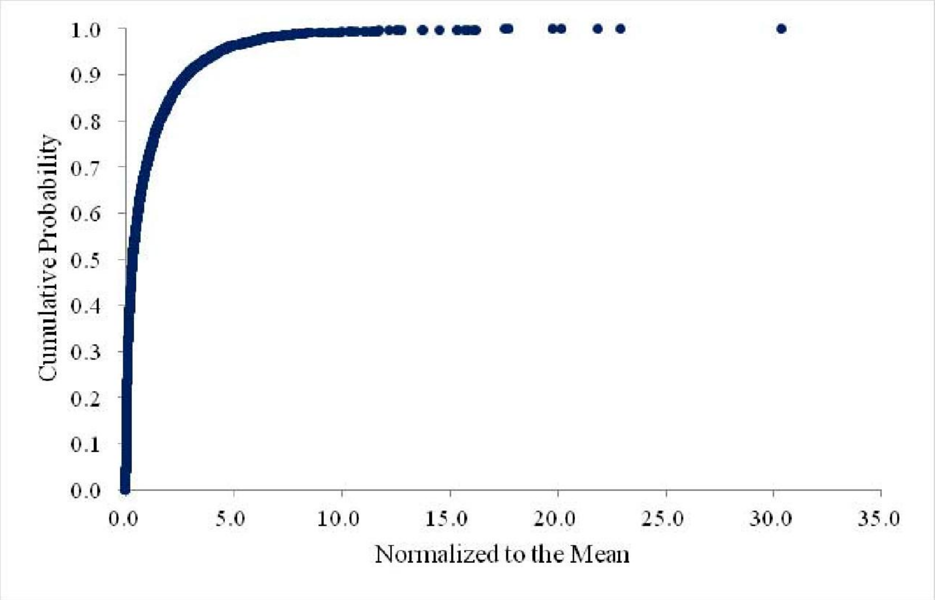

Fig. 3. Cumulative probability distribution of daily rainfall in Taipei (1981 – 2010)

Note: X- axis – normalized daily rainfall values ($rainfall_x/rainfall_{mean}$)

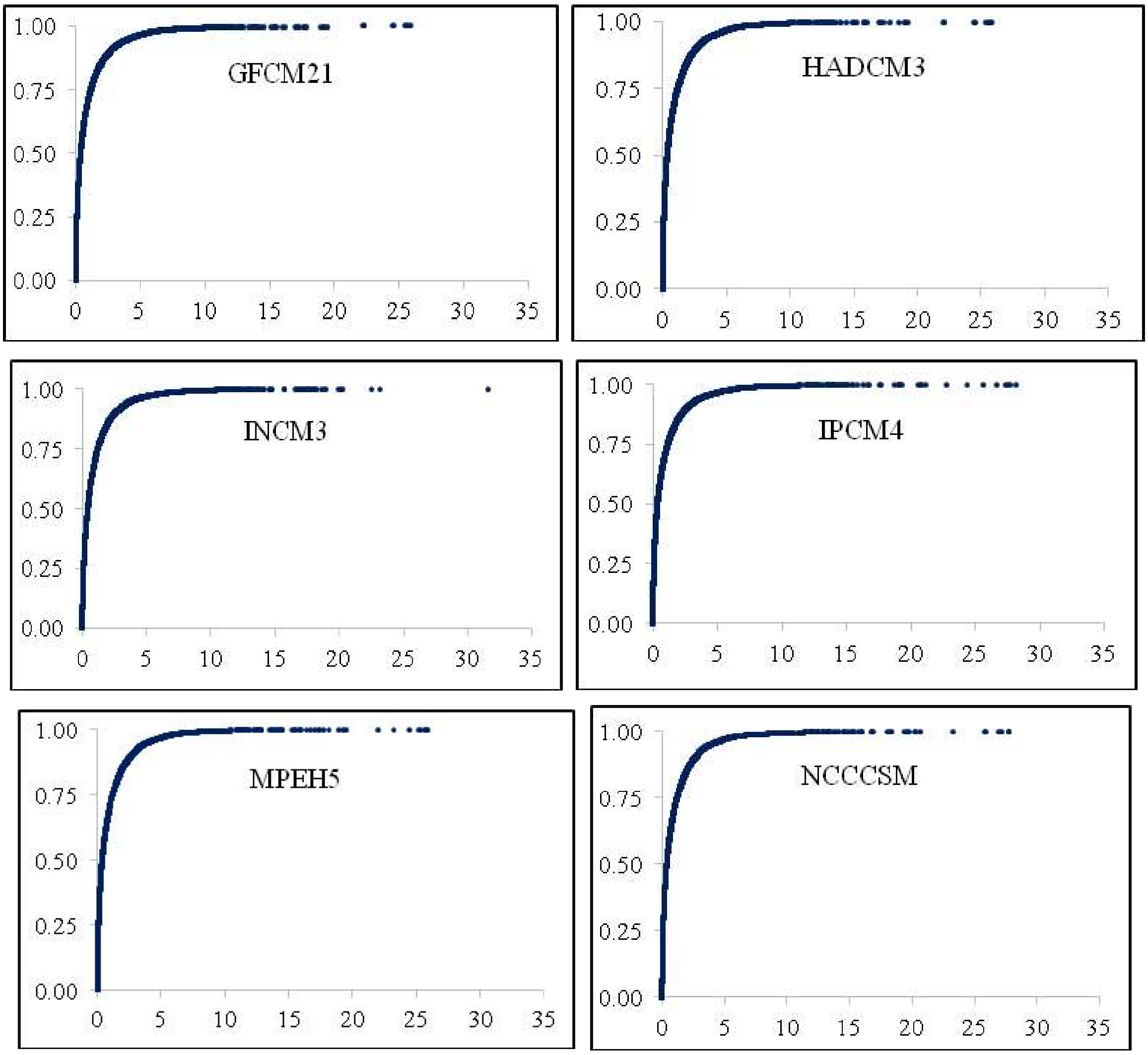

Fig. 4. Cumulative probability distribution graphs of the projected daily rainfall for Taipei study area from the selected climate models under A1B emission scenario (2011-2099). Note: X- axis – normalized daily rainfall values (rainfall$_x$/rainfall$_{mean}$)

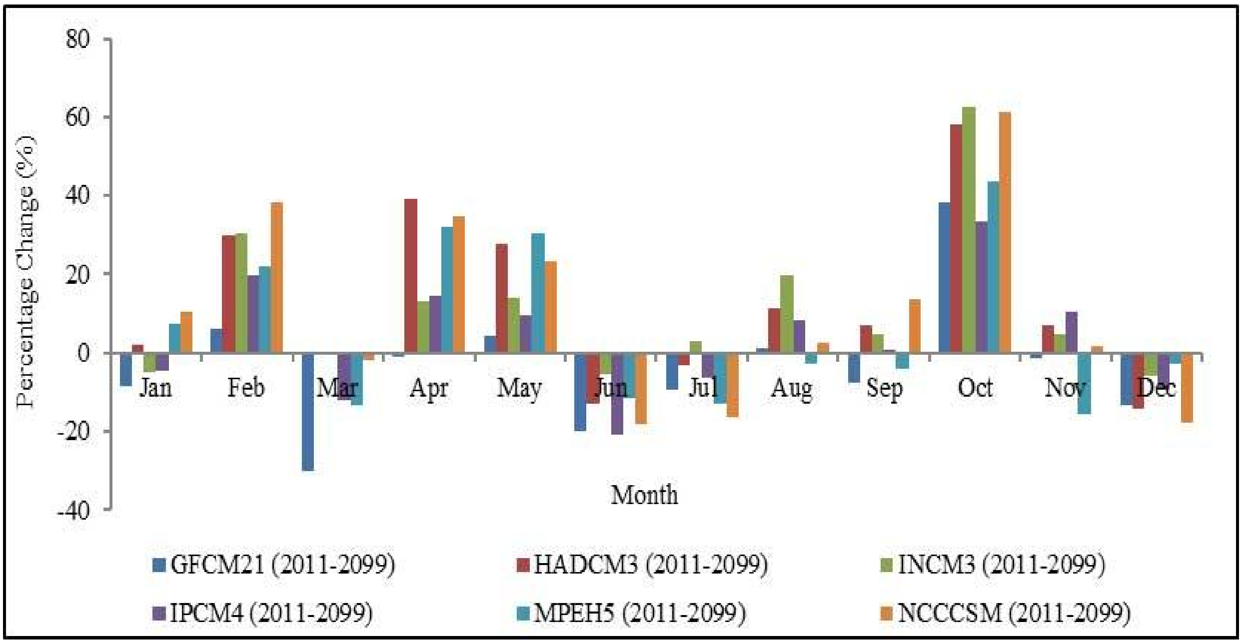

Fig. 5. Percentage variation of the mean of the daily rainfall records of Taipei study areas with reference to the historical mean values and model projections

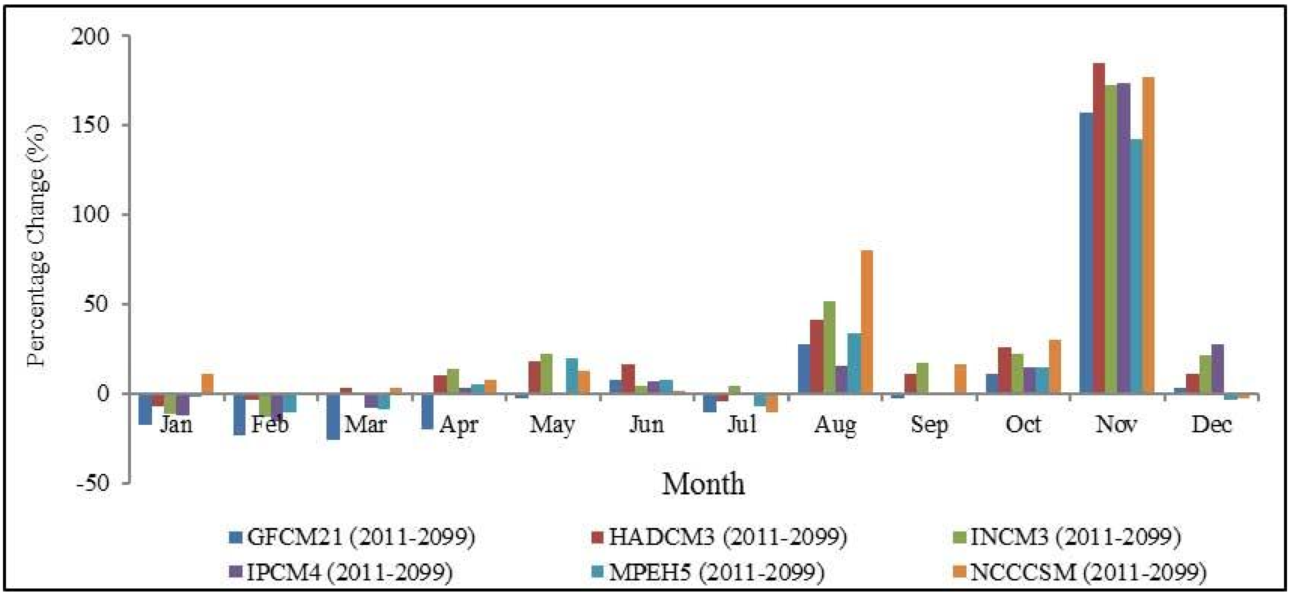

Fig. 6 Percentage variation of the maximum daily rainfall records of Taipei study areas with reference to the historical mean values and model projections

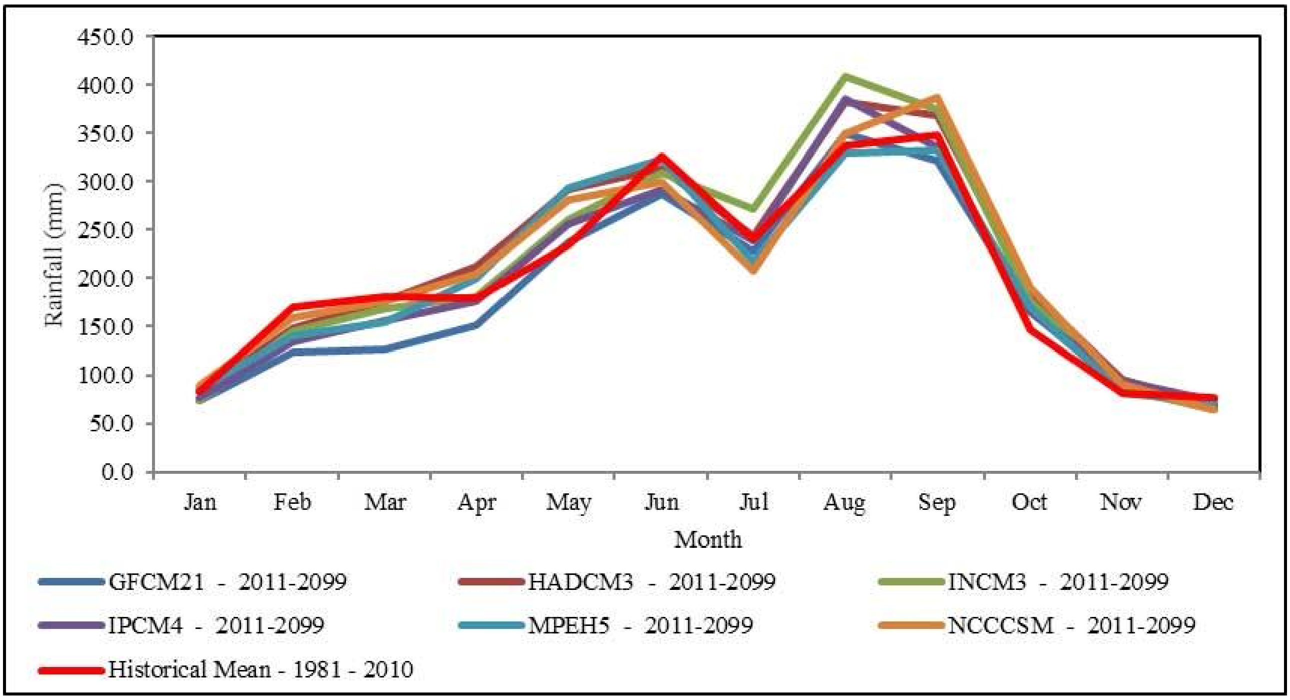

Fig. 7 Monthly rainfall variation of the Taipei weather station with the selected Climate change model outputs (2011 - 2099) for A1B emission scenario

However, each model projections have acted differently in different months. Especially during the months of May, October and November, almost all the models have projected higher monthly rainfall values. Some models have even projected almost 100 mm more rainfall. Rainfall changes in this magnitude may have a significant impact on the RWH systems. Fig. 8 shows the results of the model performance in projecting the future annual rainfall values. According to Fig. 8, the majority of the models performed in a mixed way where there are positive projections under one emission scenario while there are also negative results with another emission scenario for the same model. HADCM3 and INCM3 models have all positive changes in the rainfall projections with all the three emission scenarios in concern.

Modelling the Rainwater Harvesting System

Rainwater harvesting systems should be modelled in accordance with the water balance equation. This study considers urban households in residential context as well as with non-residential context with different storage tanks and different catchment areas as expressed in Table 2. Taking a wider range of RWH systems into consideration can capture

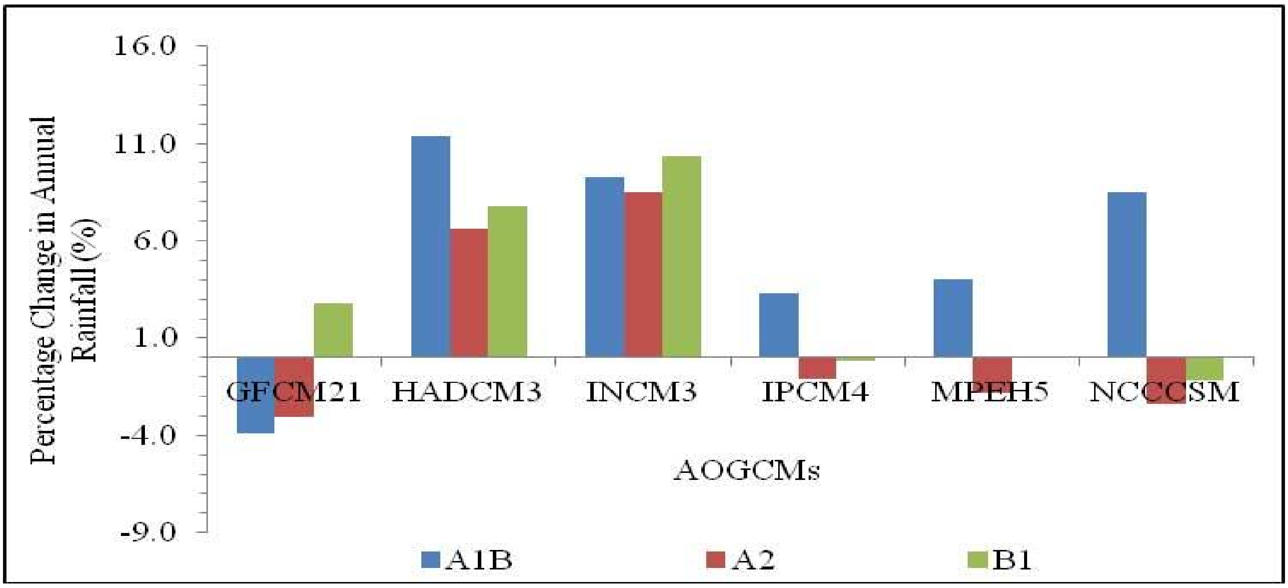

Fig. 8. Percentage change in the annual rainfall – Taipei weather station, under different climate change projection model outputs (2011 - 2099)

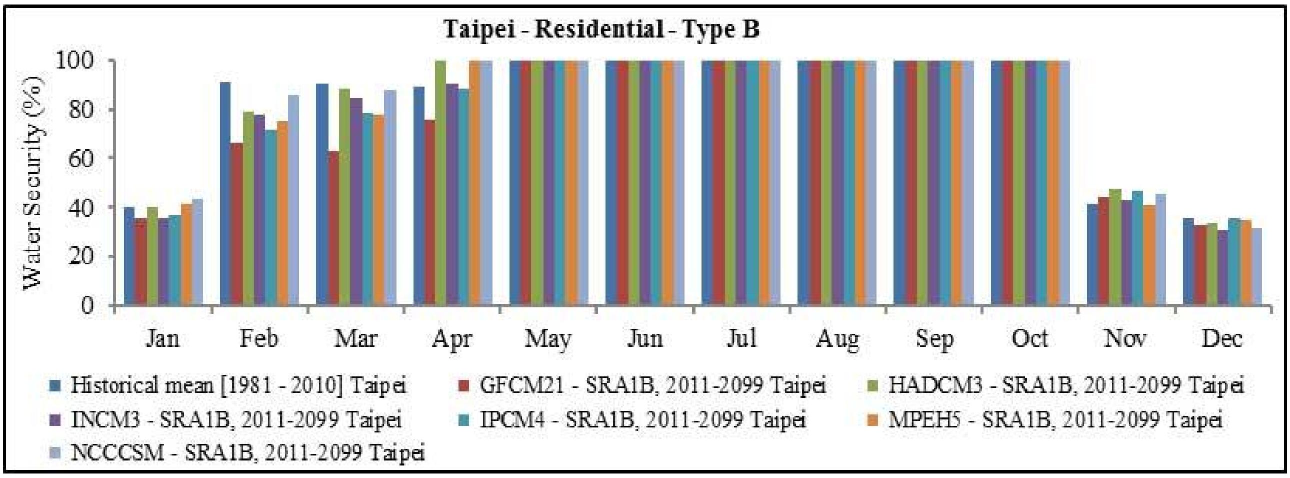

Fig. 9. Monthly water security of the RWH systems with residential - Type B Scenario, under different climate change projections

Table 4. Overall water security change (%) with respect to the each rainwater harvesting scenario type as well as climate change projections

Rainwater Harvesting System Scenario	GFCM21	HADCM3	INCM3	IPCM4	MPEH5	NCCCSM
Residential – Type A	-1.28	-0.41	-1.55	-0.50	0.03	-0.15
Residential – Type B	-5.87	0.08	-2.08	-2.48	-1.54	0.49
Non Residential – Type A	0.00	0.00	0.00	0.00	0.00	0.00
Non Residential – Type B	0.00	0.00	0.00	0.00	0.00	0.00
Non Residential – Type C - large scale (indoor)	-0.01	-0.01	-0.02	0.00	0.00	-0.02
Non Residential – Type D - large scale (outdoor)	-0.30	0.00	-0.98	0.00	0.00	-0.80

the wide range of impacts to different RWH systems. This study also has incorporated a portion of the rainwater usage in the urban landscaping and gardening. Evapotranspiration is the process responsible to remove water from fields including evaporation from the soil and transpiration from plants. Since all the urban households in this study have a portion for urban landscaping, the computation process of the outdoor water demand involves the landscape evapotranspiration value. A single series of monthly evaporation values at the study sites is used to calculate landscape evapotranspiration. The potential changes in the evaporation values in the future are not reflected upon the landscape evapotranspiration values. Six RWH system types are used to represent the entire urban community. These types should represent or cover most of the urban sector. Two scenarios to represent the low water consumption rate as well as high water consumption rate are applied to residential and non-residential types. The RWH system model has several critical aspects in regard to its performance. The most important factor is the storage tank. Once the size of the storage tank changes, the respective water securities for a given system also change dramatically. However, the storage capacities is based on the average size of the actual RWH systems in use in Taipei City. As this study focuses in the urban context, space of a RWH system is also very critical. But, with the introduction of recent new laws and regulations, RWH system is mandatory in new constructions in Taiwan. Architects and civil engineers have to try novel ways to squeeze the available space to make room for RWH systems. Nevertheless, RWH systems are still not that popular among private sectors especially in small household levels. Rainwater catchment area is also another critical element. In most cases, the rooftop is proposed as the runoff catchment space. In large-scale systems, areas with paved surfaces can be a good candidate in runoff collection for RWH systems. Water demand can be another critical factor, especially when calculating water securities. In this study, the indoor water requirement is the largest water demand among all other water requirements. Actually, the outdoor water demand is very small compared to indoor water requirement. Rainfall or water supply is also a critical element as the entire system build upon this. This study checks the system performance against the potential change in the rainfall levels due to climate change. However, due to the selection of rainfall level in monthly scale, the projected climate change are not adequately reflected in the water security analysis.

Water Security Analysis

Water security is used to evaluate the performance of a hydrological system. High water security means that the system is performing well and if the water security value is low, the system has failed to serve its intended need. Considering the monthly variation of water security, RWH systems under residential type A, B, non-residential type C and D have low water security values for all six scenarios. The rest of the scenario has 100% water security most of the time under any model projection for the given conditions. Residential type B shows less water security levels in the first few months of the year (Fig. 9). The effects of climate change on the RWH systems can be observed in terms of percentage change in the water security for each system with respect to different AOGCM model downscaled results (Table 4). It is evident from the results that out of the six scenarios, model output of GFCM21 accounts for the highest negative percentage change in water securities. This shows that the projected rainfall patterns under this model results will further deteriorate the water securities of the RWH systems.

Except for the residential type B scenario, most of the other model outputs have resulted in either negative or neutral percentage water securities change. These negative changes are relatively small except with the GFCM21 model results. For the residential type B scenario, the projected model results show better water security level improvements (except for the GFCM21 model). Obviously residential type B works well under most climate change projections, whereas the other types perform less favourably or have neutral effect. In other words, the performance of RWH systems differs a great deal according to their configurations. Also, it is essential to plan and design the RWH system along with possible climate and rainfall pattern changes. Overall results point to the fact that this study is able to detect possible future rainfall changes based on the six AOGCM model outputs. Impacts of these possible future rainfall changes on the RWH systems are also inevitable. However the impacts on the RWH systems in Taipei tend to be small in magnitude because this study detects the impacts based on monthly water security levels. Daily water security changes may be able to provide better results.

CONCLUSIONS

The RWH system responses on the urban scale in Taipei City have been explored and evaluated according to possible future climate change scenarios. Results using statistical downscaling of large-scale atmospheric variables simulated by six AOGCM climate change models under the A1B, A2 and B1 emission scenarios with local scale rainfall are obtained. Under A1B emission scenario, the long-term annual rainfall trend for the next century (2011-2099) in Taipei shows a decreasing trend. However, when considering the percentage changes of the rainfall for the next century, two out of six model results show a positive percentage change in annual rainfall. Results further reveal that several extreme weather events with very heavy rainfall may occur in the future. However, the frequency of these big events may not occur too often.

This study also discovers that all types of RWH systems are affected by the projected future rainfall, when there is large water demand and/or the storage capacity of the system is limited. Using monthly rainfall data to calculate the storage requirement often underestimate the required storage capacity. Daily rainfall data for RWH storage calculations is highly recommended. When considering the overall RWH systems, the residential sector RWH is more affected than non-residential sector systems. The climate change impacts on the RWH systems are inevitable. Mitigation steps should be incorporated in the initial phase of the system design to reduce these impacts. Considerable variation on rainfall pattern changes and degree of severity is found in the Taipei study site. Climate change can affect the hydrological performance of RWH systems in Taipei. The current rate of urbanization in Taiwan will result in higher demands for resources, including the access of water. RWH is a viable option if it is incorporated with possible future climate change impact design.

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