Rainwater Harvesting for Domestic Water Supply and Stormwater Mitigation

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Abstract

Supplying sufficient water to meet the ever-increasing water demands of the population, and to ensure equitable access to water, is one of the most urgent and important challenges faced by most decision-makers in urban areas. Previous studies have demonstrated that urbanization gradually alters urban watershed hydrology by increasing both the quantity and peak of stormwater runoff to receiving water.

Rainwater harvesting is a decentralized environmentally sound method of augmenting freshwater resources, and can avoid the environmental problems that often result from centralized, conventional, large-scale project approaches. Rainwater harvesting decreases the demand in urban areas, and also the runoff that floods and pollutes our oceans, rivers and lakes. Lowering the amount of runoff after a storm recharges the groundwater by giving the earth an opportunity to absorb the water that has fallen.

This study firms up the promotion of rainwater harvesting and utilization technology in water supply and stormwater mitigation on a regional basis. The study area is divided into four regions, which are determined by amount of rainfall and rainfall patterns. The average annual rainfalls are about 1769.1mm in region I; 2959.7mm in region II; 2034.8mm in region III, and 3413.7mm in region IV. The capacity design curves for roof-top rainwater catchment system for different rainwater substitution ratios in different regions are also established. The rainwater storage capacity of a site is selected first to provide sufficient water demand, then to maximize efficiency in reducing stormwater. The relationship between the runoff volume/peak flow and percentage area required to construct roof-top rainwater harvesting for various CN values are established for the selected stormwater mitigation efficiency. The XP-SWMM model is then used to simulate the runoff volume and peak flow for various CN values. Nan-Hi community in northern Taiwan is selected to verify the results obtained by this study.

Introduction

Global population has more than doubled since 1950, reaching 6 billion inhabitants in 1999. The most recent population forecasts from the UN indicate that global population is likely to peak at about 8.9 billion in 2050 in a medium-fertility scenario. Corresponding to these changes, profound demographic shifts as people continue to migrate from rural to urban areas in search of work and new opportunities. The number of urban dwellers has jumped from 750 million in 1950 to more than 2.5 billion people. [Some 61 million people are currently being added to cities each year through rural-to-urban migration, natural growth within cities and the transformation of villages into urban areas. The total urban population is projected to double to more than five billion by 2050, and 90% of this growth is expected to occur in developing countries.

The most urgent and significant challenges faced by most decision-makers are Supplying adequate water to meet the ever-increasing water demand due to population growth, and ensuring fair access to water in urban areas. Two solutions are available to satisfy sustainable freshwater management: (1) finding alternative or additional water resources using
conventional centralized approaches, and (2) using the limited water resources available more efficiently. Rainwater harvesting and utilization is a decentralized, environmentally sound way of augmenting freshwater resources. It can avoid many environmental problems, which are often created by using centralized, conventional, large-scale project approaches.

Urbanization has also been shown to gradually alter urban watershed hydrology by increasing both the quantity and the peak of storm water runoff to receiving waters. This phenomenon causes direct and cumulative adverse impacts on the physical, chemical and biological integration of aquatic ecosystems. Development impacts are typically prevented and mitigated by structural and non-structural methods, such as rainwater harvesting, wetland, detention a/o retention ponds and infiltration facilities. Rainwater harvesting systems are managed in small, cost-effective features located at each lot rather than being conveyed and managed in large, costly pond facilities located at the bottom of drainage areas. The source control concept is quite different from conventional end-of-pipe treatment.

Rainwater harvesting systems decrease the demand for city water in urban areas. They also reduce the amount of runoff that floods and pollutes the oceans, rivers and lakes. Lessening the amount of runoff after a storm recharges the groundwater by giving the earth an opportunity to absorb the water that has fallen. This study investigates the extent to which storage volume of rainwater harvesting systems increases water supply and reduces the amount of on-site rainwater volume and peak at developed sites in urban areas.

Feasibility of Rainwater Harvesting in Urban Environments

Rainwater harvesting has conventionally been considered as a potential water supply source in remote rural settlements where the provision of water through piped networks is uneconomic or not technically feasible. However, rainwater harvesting in urban settlements has gained momentum due to the recognition that usage of water where it falls has both economic and ecological advantages.

Rainwater harvesting systems are increasingly widespread in Germany and Japan, where several firms now offering compact off-the-shelf rainwater use systems. One million people in Australia also rely on rainwater for their water supply. The government of South Australia promoting rainwater collection by providing information on cistern sizing, materials and maintenance to the general public and interested parties. In the, Ede, in the east of the Netherlands, is the first municipality in the country to introduce a dual water system, after small experiment in various other cities. The system in Ede is to be introduced in a new estate of 3500 houses over the next ten years. The houses will be constructed with one pipe for their drinking water, and a separate pipe filled with rainwater for activities such as flushing the toilet, doing the laundry and watering the garden. The local energy company will construct the dual net, which is expected to reduce the use of expensive drinking water by 50%. In higher parts of the municipal area, rainwater will be obtained per house or block of houses in water containers, sand reservoirs and underground reservoirs. In low-lying areas, rainwater will be collected in ponds.

Scientists and city planners worldwide are beginning to understand the vulnerability of the central infrastructures of modern cities to earthquakes and natural hazards. The municipal water supply is one of the most vulnerable parts of a city infrastructure. Hence, permanent rainwater reserves are essential in helping a city survive earthquakes and natural hazards.

Assessment of Rainwater as a Potential Water Supply Source

Rainwater supply systems in the urban areas can be successfully utilized not only in individual households, but also other buildings such as those listed below:
1. Blocks of flats
2. Offices and commercial complexes
3. Hotels
4. Prisons
5. Industrial complexes and power plants
6. Large Institutions such as school campus and parks.

The three major parameters in the design of rain water tanks are the contribution area, the rain water consumption rate and the tank volume. The most important design evaluation criterion is the reliability of the supply.

Development of a Reference Map or Computer Tools for Sizing of Storage Volume for Rainwater Harvesting Systems

Rainwater harvesting can be impossible or impractical when rainfall data or computation models are not available. A reference map or computer tools are required to solve this problem.

Development of Storage Sizing Reference Map

Rainfall stations that have been recording rainfall data for over 50 years throughout the country were selected to calculate the storage capacity under specific roof areas and the reliability of the water supply. Rational water demand was assumed. A series of storage sizing reference maps was generated for various roof areas and water supply reliabilities. The map indicates that storage capacity can be estimated for a given set of design criteria. These sizing maps can be employed as a quick reference for designing rainwater harvesting systems.

Rainfall Zones and Regional Storage Sizing Computer Model

Several computer programs are available to determine tank sizes quite accurately. However, a design based on any single statistical indicator can be misleading if the rainfall shows large fluctuations. Therefore, a computer model that considers fluctuations in rainfall should be developed. The proposed model is designed in the following manner. Rainfall stations are located on the map of the region to which rainfall normally are assigned. Areas of similar rainfall amounts and distribution patterns are subsequently identified, and boundaries are delineated through the use of iso-lines. Each zone is given a numeric designation referring to a specific storage sizing formula.

Rainfall records are available on a monthly and a daily basis, although considerably more effort is required to process daily data for analyzing the performance of the collection system. Additionally, the Yield Before Spillage (YBS) model, based on the Yield After Spillage (YAS) model, is proposed to compensate for an apparent loss of efficiency due to spillage when storage before spillage occurs. This modifies the Yield After Spillage (YAS) model.

Having selected the model, the system performance can be evaluated for each time interval of the record by water supply reliability. To facilitate presentation of performance characteristics as a function of demand and storage, demand and storage is conveniently expressed in a non-dimensional form. Demand and storage divided by the supply of rainfall is a non-dimensional demand parameter, and lies in the range from zero to 100%.

Types of Water Storage Structure and Their Selection
Rainwater storage reservoirs can be subdivided into three distinct categories:
1. surface (above-ground tanks), which are common in roof catchment systems, where the catchment surface is elevated e.g. for roof catchments;
2. sub-surface or underground tanks, which are normally associated with purpose-built ground catchment systems, and
3. dams with reservoirs for larger catchment systems using natural catchment, e.g. rock catchment, earth dams and sub-surface or sand dams in sand rivers.

**Rainwater Harvesting for Flood Mitigation**

Generally, most of the rainwater from impervious areas in the urban areas is passed through sewer systems. Therefore, using rainwater in the home can be a good option to tackle this problem. The rapidly drained rainwater leads to problems in the sewer systems and watercourses, which cannot handle very high peak discharges. If the storage in the rainwater tanks can be used to flatten the rainwater runoff, then the rainwater tanks can have additional benefit. Rainwater tanks need much more storage to obtain the same overflow frequency than downstream storage, since the storage in rainwater tanks is less frequently available. Rainwater tanks can certainly be promoted as a good solution when considering all the economical, social and environmental aspects are considered.

**Storage Volume Design**

The required capacity to maximize the water savings and rainwater management depends on water use, rainfall and roof area. The rainwater tank design should provide for:
1. A minimum availability volume (to ensure that water supply is always available or emergency water use).
2. A rainwater storage volume (to provide a regular water supply).
3. A space to handle excess rainwater.

**Hydrological Effect of Rainwater Harvesting Systems**

Rainwater storage allows for a reduction in rainwater volume and the peak runoff rate. The fundamental parameters of rainwater harvesting systems affecting site hydrology are as follows:
1. Change curve number (CN): a factor that accounts for the effects of soils and land cover on the amount runoff generated.
2. Change time of concentration: the time taken by the runoff to travel through the watershed.
3. Change design storm: the outflow of the rainwater tank can be converted to equivalent rainfall. The original design storm is corrected with this reduction correction.

**Hydrological Analysis of Distributed Rainwater Harvesting Systems**

*Theory and Computational Procedures*

The hydrological analysis of distributed small-scale rainwater harvesting systems is a sequential decision making process, and is illustrated by the flowchart in Fig. 1. The procedures for each step are given in the following sections. Determination of rainwater storage volume to maintain the existing volume and peak runoff rates to satisfy rainwater
management requirements are studied and discussed in the following sections.

Figure 1 Planning procedure of small-scale distributed rainwater harvesting control systems

The basic information used to develop the distributed small-scale rainwater harvesting systems management plan and used to determine the runoff curve number and time of concentration for the pre- and post-development condition is the same as that described in TR-55.

**Determine Storage Volume Required to Maintain Runoff Volume**

The rainwater storage volume is required to control the increase in runoff volume if runoff volume reduction cannot reach the acceptable level. The post-development runoff volume generated as a result of the post-development custom-made CN is compared to the pre-development runoff volume in order to determine the volume required.

**Determine Storage Volume Required to Maintain Peak Runoff Rate**

Rainwater harvesting systems retains a permanent pool. The storage volume provided is used to control the runoff peaks caused by the specified designed storm events. The designed capacity of rainwater storage volume generally accumulates until the inflow equals pre-development peak at recession of inflow hydrograph. No outflow passes through the storage tank before the inflow reaches the pre-development peak flow. Therefore, the volume required to maintain the peak runoff rate using rainwater harvesting systems is greater than the requirement for detention ponds.

If the storage volume required to maintain the pre-development peak runoff rate using rainwater harvesting systems is less than that in the last step, then no additional detention storage is needed; otherwise, additional detention storage is needed.

**Determine Storage Volume Required to Maintain Peak Runoff Rate Using 100% Detention**
Suppressing peak flow to a given degree during a given design storm requires a certain
definite amount of storage. The required detention volume is determined with the basic
storage equation. Storage accumulates as long as the inflow is greater than the outflow, and
stops accumulating when the inflow falls below the outflow. The maximum storage is the
required storage volume of the detention basin. This is represented in the hydrograph by the
area between the high inflow and low outflow curves. This method can be applied to
determine the inflow, outflow and detention storage volume for selected increments of time
during the storm event.

*Use Hybrid Facility Design (Required for Additional Detention Storage)*

A hybrid approach, defined as the combination of retention and detention practices, must
be used when the percentage of site area for peak control exceeds that for volume control as
determined in step 3.

*An Illustrated Example*

To demonstrate the application, a user-friendly computer-based model for estimating
storage volume based on design criteria and a series of design charts for estimating the
detention/retention storage volume required for different CN values change, were developed
in this research. In the following example, rainwater storage is used for storm water runoff
control will be discussed. Nan-Hi community is an old community and locates at the northern
part of Taipei city. It has frequent flooding in recent years and its stormwater sewerage system
as shown in the following figure. As limited space forbids it to install pumping station and
expand stormwater sewerage system. Therefore, rainwater storage is another alternative
solution. In this study, rainwater storage volume required is estimated using the charts
developed in this study and XP-SWWM model is used following to examine the improvement
of flooding condition.
Economic Benefits Incurred by Integrated Systems

Establishing and combining these cheap rainwater harvesting systems with existing water supply and flood mitigation systems has a considerable impact on both the rising demands and savings in deferred capital costs for both water supply and flood control. These systems can replace conventional projects, which can therefore be postponed. Capital investment can therefore be delayed, producing considerable savings for the water authorities.

In general, rainwater harvesting systems can affect facilities by:

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<th>Basin</th>
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<th>Building B</th>
<th>Basin Area</th>
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<tr>
<td>Basin4-303</td>
<td>220 m²</td>
<td>20 m²</td>
<td>800 m²</td>
</tr>
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</table>

Figure 2 Layout of buildings and stormwater sewerage system in Nan-Hi community
1. Eliminating the need for facilities;
2. Delaying construction, and
3. Reducing the size of the facilities.

**Discussions and Conclusions**

The relentlessly expansion of urban development and the emergence of megacities, especially in developing countries, means that small rainwater harvesting systems should be implemented in all possible sites, and that these schemes should be designed multi-objectively, integrated with existing conventional schemes and operated optimally. Rainwater harvesting systems employ small-scale and distributed management practices to achieve the desired peak runoff rate and runoff volume. Additionally, many upstream and downstream controls for managing urban flood are available. The economic performance of this control can be evaluated by estimating the benefits of the outputs and the costs of the inputs. While optimal solutions can be determined for complex blends of on-site and off-site controls, the transaction costs of deciding how to pay for such complex systems may offset the gain in economic efficiency.

**References**