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HYDROLOGIC ANALYSIS OF DISTRIBUTED SMALL-SCALE STORMWATER CONTROL SYSTEMS

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SYNOPSIS

The conventional stormwater management requirement is usually to maintain the peak runoff rates at pre-development levels for a particular design storm event. This type of design does little to reduce runoff volume and may even exacerbate stream erosion problems at downstream. Distributed small-scale stormwater control systems is an alternative method for stormwater control, and employs small scale and distributed management practices to achieve desired post-development peak runoff rate and runoff volume. The purpose of this study is to provide hydrologic analysis and computation procedures used to determine distributed small-scale stormwater management requirements. The hydrologic analysis presented is based on the Soil Conservation Service (SCS) method. Computational procedures for determining this innovative stormwater management requirement are demonstrated by means of the illustrative example.

INTRODUCTION

Typical alterations to the hydrologic regime as a result of local development and the related increase in impervious areas include, but are not limited to, the following: (1) increased runoff volume; (2) increased flow frequency, duration, and peak runoff rate; (3) reduced infiltration; (4) modification of flow patterns; (5) faster time to peak, and (6) loss of storage.

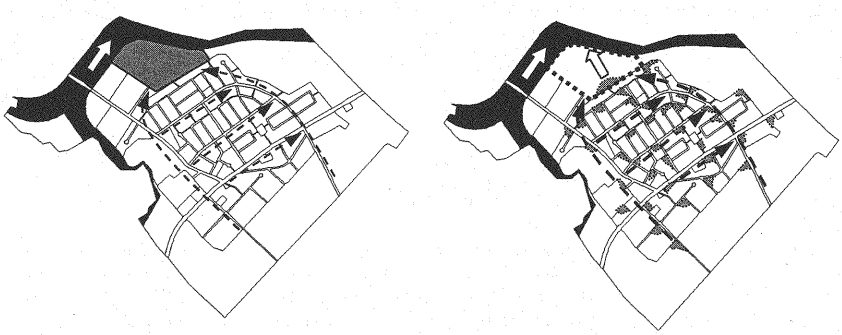
As urban development expands relentlessly, the need for effective stormwater management technology has never been greater. One of the most common ways of minimizing downstream flood-risk as a result of new urban development is by means of runoff detention ponds. They are typically sited at the most downstream point of the developed site and runoff may be stored temporarily to reduce the peak rate of runoff prior to entering the receiving water. In doing so, traditional conveyance/storage drainage systems coupled with the impervious surfaces tend to increase downstream flooding and to prolong high storm flows. This may cause stream erosion, and deliver nonpoint source pollution to receiving waters during smaller events (Heaney, et al. (3), Walesh (8)).

As an alternative stormwater management strategy; that is the use of distributed small-scale stormwater control practices (as shown in Table 1) has been proved to be getting the great environmental benefit which is associated with retaining and infiltrating runoff throughout the developed area. Fig. 1 shows the difference between these two approaches. Distributed small-scale stormwater control systems control stormwater at the source by creating a hydrological functional landscape that simulates natural watershed hydrology (Liaw, et al. (4)). It employs small scale and distributed management techniques to achieve desired post-development hydrologic conditions and tries to simulate these mechanisms by uniformly distributing small infiltration, storage, retention, and detention measures throughout the developed area. In comparison with conventional stormwater management, the objective of hydrologic design of distributed small-scale stormwater control systems is to retain the post-development excess runoff volume in discrete units throughout the site to emulate the pre-development hydrologic regime. The purpose of this approach is to manage runoff at the source rather than at the end-of-pipe. Preserving the hydrologic regime of the pre-development condition may require both structural and nonstructural techniques to compensate for the hydrologic alterations of development.

There is increasing interest in study of this alternative. This study briefly outlines distributed small-scale stormwater control systems and discusses its basic hydrological control principles. Combination principles of distributed small-scale stormwater control facilities will be investigated and system simulation will be used for watershed stormwater management studies.

Table 1 Small-scale distributed stormwater control systems and hydrologic design and analysis components

Small-scale distributed stormwater control system / Hydrologic design and analysis components	Site design practices								Small-scale distributed stormwater control facilities							
	Flatten slope	Increase flow path	Increase sheet flow	Increase roughness	Minimize disturbance	Constricted pipes	Disconnected impervious areas	Reduce curb and gutter	Flatten slopes on swales	Infiltration swales	Vegetative filter strips	Rain barrels	Rooftop storage	Bioretention	Revegetation	Vegetation preservation
Lower post-development CN					●		●	●		●	●			●	●	●
Increase Tc	●	●	●	●		●	●	●	●		●	●	●	●	●	●
Retention										●	●	●	●	●	●	●
Detention						●			●			●	●			



(A) End-of-pipe control (B) Distributed control approach

Note. Shadow areas represent end-of-pipe and distributed control facilities.

Fig. 1 Comparison between conventional and distributed control of stormwater management

SUITABILITY OF EXISTING STORMWATER MODELS

To implement distributed small-scale stormwater control systems concepts on a broad scale, analysis tools should include some level of process simulation to take into account site-specific factors that influence performance. Two types of commonly used runoff estimation methods are briefly summarized and discussed below:

Unit Hydrograph

The Unit Hydrograph (UH) has long and successful history in rainfall/runoff estimation. The rational method is a special case of the UH method (Hall (2)). The UH is a linear transform function that is applied to a time series of rainfall, resulting in an output hydrograph (Bedient and Huber (1)). The ordinates of the UH are generally obtained from measured sets of rainfall and runoff. However, hydrologic process information is only implicitly included in the ordinates of the transform. They have no direct physical meaning. The UH method is inadequate for the simulation of controls that are designed to alter the hydrology. Therefore, the UH method, like the rational method, appears to be unsuitable for distributed small-scale stormwater control systems process modeling.

SCS Method

The SCS method was developed and documented by the U.S. Soil Conservation Service. While the SCS method may be characterized as an extension of UH method (McCuen (5)), it shows more promise for distributed small-scale stormwater control because soil moisture storage is explicitly treated (Mishra and Singh (6), U.S. Department of Agriculture (7)). The SCS method is sensitive to site-specific conditions, and a great deal of data (generally based on soils, slope and land use) is available. Various surface conditions may be simulated.

The following relationship is mathematical expression of the SCS hypothesis:

$$P_e = (P-0.2S)^2/(P+0.8S) \quad (1)$$

where P_e = direct runoff (mm); P = the depth of design storm (mm); and S = the potential maximum retention (mm). The empirical analysis revealed the following relationship:

$$S = 25400/CN - 254 \quad (2)$$

The curve number (CN), an index of land use and soil types, is used in many hydrologic analysis techniques. Soil types are classified into four hydrologic soil groups (HSG's) according their minimum infiltration rates (U.S. Department of Agriculture (7)).

Due to its widespread use and available soil database, the SCS method is well suited for initial screening of distributed small-scale stormwater control systems.

HYDROLOGIC EVALUATION

The distributed small-scale stormwater control systems analysis and design approach focus on the following three major elements. These fundamental factors affect surface water hydrology and are discussed below (Liaw, et al. (4)).

Minimizing the Change in CN and Maintaining the Pre-development Time of Concentration (T_c)

Reducing the change in CN alone will reduce both the post-development peak discharge rate and volume. The hydrologic evaluation at on-site design practices requires that the post-development Tc be close to the pre-development Tc. Fig. 2(A) illustrates the hydrologic response to maintain equal pre- and post-development Tc.

- Hydrograph 1 represents the response of a pre-development condition.
- Hydrograph 2 represents the response of a post-development condition without stormwater management.
- Hydrograph 3 represents the resulting post-development hydrograph using the on-site design practices to reduce impervious area and increase storage volume.
- Hydrograph 4 represents the effects of the on-site design practices to maintain the Tc.

This effectively shifts the post peak runoff time to that of the pre-development condition and lowers the peak runoff rate.

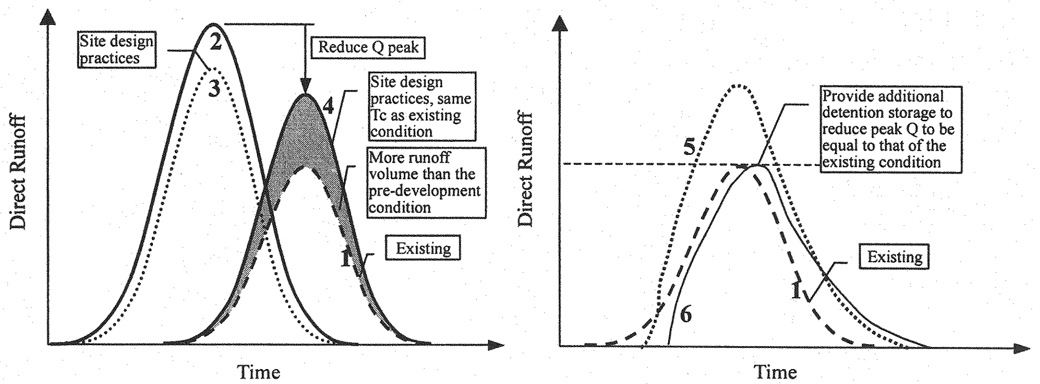
Maintaining the Pre-development Runoff Volume

Once the post-development Tc is maintained at the pre-development conditions and the change of pre-development to post-development CN is minimized, any additional reductions in runoff volume must be accomplished through distributed on-site stormwater management techniques. Retention storage allows for a reduction in the post-development volume and the peak runoff rate.

Potential Requirement for Additional Detention Storage

In cases where very large changes in CN cannot be avoided, retention storage practices alone may be either insufficient to maintain the pre-development runoff volume or peak discharge rates, or require too much space to represent a viable solution. In these cases, additional detention storage will be needed to maintain the pre-development peak runoff rates. The effect of this additional detention storage is illustrated in Fig. 2(B).

- Hydrograph 5 represents the response of a post-development condition that incorporates retention distributed small-scale stormwater control facilities.
- Hydrograph 6 illustrates the effect of providing additional detention storage to reduce the post-development peak discharge rate to pre-development conditions.



(A) Site design practices hydrograph that has a reduced CN and maintains the Tc

(B) Effect of additional detention storage on retention practices

Fig. 2 Hydrograph analysis of distributed small-scale stormwater control systems

THEOREY AND COMPUTATIONAL PROCEDURES

The hydrologic analysis of distributed small-scale stormwater control systems is a sequential decision making process that can be illustrated by the flow chart in Fig. 3. The procedures for each step are given in the following sections. Determination of storage volume to maintain the existing volume and peak runoff rates to satisfy stormwater management requirements will be investigated and discussed in the next section.

Data Collection

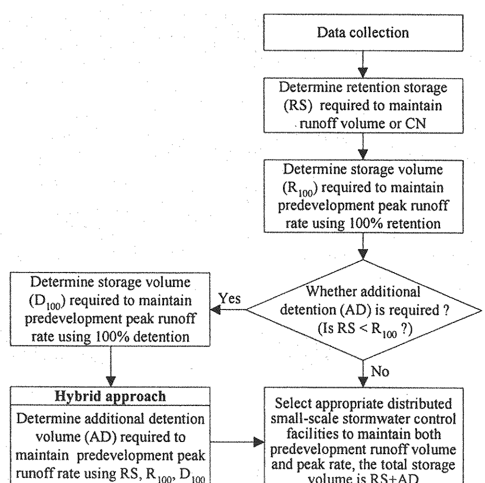


Fig. 3 Planning procedure of small-scale distributed stormwater control systems

The basic information used to develop the distributed small-scale stormwater 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 the TR-55 (U.S. Department of Agriculture (7)). They include detailed land cover and hydrologic soils groups within the development site. The criteria used to select the design storm that includes amount and distribution is based on the goal of maintaining the pre-development hydrologic conditions for the site. The remaining distributed small-scale stormwater control systems are based on the premise that the post-development Tc is the same as the pre-development condition. If the post-development Tc does not equal the pre-development Tc, additional on-site design practices must be implemented to maintain the Tc.

Determine Storage Volume Required to Maintain Runoff Volume Using Retention Storage

Even with on-site design practices, storage volume is required to control the increase in runoff volume using retention facilities 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 to determine the surface area required for volume control. The retention volume (RS) for maintaining pre-development runoff volume can be determined as:

$$RS = [(P-0.2S_{PostDEV})^2/(P+0.8S_{PostDEV})-(P-0.2S_{PreDEV})^2/(P+0.8S_{PreDEV})]DA \quad (3a)$$

$$S_{PostDEV} = f(CN_{PostDEV}) \quad (3b)$$

$$S_{PreDEV} = f(CN_{PreDEV}) \quad (3c)$$

where P = the depth of design storm; $S_{PostDEV}$ and S_{PreDEV} = post- and pre-development potential maximum retention, respectively; $CN_{PostDEV}$ and CN_{PreDEV} are post- and pre-development CN values, repectively; and DA = the development area.

Determine Storage Volume Required to Maintain Peak Runoff Rate Using 100% Retention

Retention basins or wet ponds retain 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 retention basins generally accumulates until inflow equals to pre-development peak at recession of inflow hydrograph. Before inflow reaches the pre-development peak flow, no outflow passes through the retention basin. Hence, the volume required to maintain the peak runoff rate using retention is greater than the requirement for detention.

If storage volume required to maintain pre-development peak runoff rate using 100% retention is less than that in step 2, no additional detention storage is needed; otherwise, additional detention storage is required.

Determine Storage Volume Required to Maintain Peak Runoff Rate Using 100% Detention

During a given design storm, to suppress peak flow to a given degree requires a certain definite amount of storage. Derivation of the required detention volume is based on the basic storage equation. Storage is accumulates as long as inflow is greater than outflow. It stops accumulating when inflow falls below 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. By this method, inflow, outflow, and detention storage volume can be computed for selected increments of time and accumulated over the duration of the storm event.

Use Hybrid Facility Design (Required for Additional Detention Storage)

When the percentage of site area for peak control exceeds that for volume control as determined in step 3, a hybrid approach that is defined as the combination of retention and detention practices must be used. The total storage volume of the hybrid area site (V_{hybrid}) is equal to storage volume required to maintain pre-development peak runoff rate using 100% detention (D_{100}) when the percentage of retention storage to total storage (x) equals to zero. When x is equal to 100%, the total storage volume of hybrid area site (V_{hybrid}) equals to storage volume required to maintain pre-development peak runoff rate using 100% retention (R_{100}). Therefore, if there is a linear relationship between the storage volume to maintain the peak pre-development runoff rate using 100% retention and 100% detention, the relationship between V_{hybrid} and x can be expressed as:

$$V_{hybrid} = (R_{100}-D_{100})x/100 + D_{100} \quad (4)$$

Eq. 4 can also be expressed as:

$$(R_{100}-D_{100})x^2/100 + D_{100}x - 100RS = 0 \quad (5)$$

in which

$$x = [50/(R_{100}-D_{100})]\{-D_{100}+[D_{100}^2+4(R_{100}-D_{100})RS]^{0.5}\} \quad (6)$$

Hence, the additional detention needed to maintain peak discharge can be determined as:

$$AD = V_{hybrid} - RS \quad (7)$$

where AD = additional detention volume required to maintain pre-development runoff peak.

The required storages for distributed small-scale stormwater control facilities can be presented as a depth over the development site. Eq. 8 is used to determine the volume required for retention facilities.

$$\text{Volume} = d_{max}\, A_{dmax}\, DA \quad (8)$$

where d_{max} = maximum allowable design depth that is determined by soil textures and ponding or storage time (T_p); A_{dmax} = percentage of site area for facilities at d_{max}. The stored runoff within the facilities should be completely drained during the ponding time. The use of the maximum allowable ponding time in conjunction with a specific soil minimum infiltration rate (f) will dictate the maximum allowable design depth (d_{max}) of the facilities. This relationship can be defined as:

$$d_{max} = f\, T_P \quad (9)$$

Percentage of site required for distributed small-scale stormwater control facilities for depths other than maximum allowable design depth can be modified as Eq. 10 shows:

$$\text{Percentage of site area for alternative depth} = A_{dmax}\, d_{max} / \text{Alternative depth of storage} \quad (10)$$

Reducing surface area requirements by considering loss can be determined by using Eq. 11.

$$\text{Volume of site area for facilities} = (\text{Initial volume})(100\text{-loss})/100 \quad (11)$$

where loss = a percentage of the storage volume infiltrated and/or reduced by evaporation or transpiration.

ILLUSTRATIVE EXAMPLE

Site Selection

The Hsi-chih area is located in the northeast of Taipei city in northern Taiwan. The area of Hsi-chih is 72km^2. Most of Hsi-chih area is hilly terrain, with narrow plains along the Keelung River (as shown in Fig. 4). The population increased by 66.43% from 1988 to 1997. Urbanization caused heavy flooding but it is difficult and expensive to acquire the land for large-scale flood control structures. To demonstrate the application of theory developed above, Hsi-chih area was selected.

The rainfall depth of design storm for 24 hours with 5 years return period is 314 mm in Wu-du rainfall station. Here, development area was assumed 300ha. The soils in the watershed are classified hydrologically as type B according to the geomorphic data. If the ponding time was assumed 48 hours, the depth of pond (d_{max}) equaled to 0.634m. Seven different 24-hr rainfall distribution types, which were shown in Fig. 5 in Taiwan, were obtained by Young etc. (9). For conservative consideration, the type VI rainfall distribution was adopted in this study.

Determine Storage Volume Required to Maintain Pre-development Volume Using Retention Storage

From Eqs. 3, 8, and 9, percentage of development area for facilities to maintain pre-development volume can be expressed as:

$$\text{Percentage of site area for facilities} = [(P-0.2S_{PostDEV})^2/(P+0.8S_{PostDEV})-(P-0.2S_{PreDEV})^2/(P+0.8S_{PreDEV})]/fT_P \quad (12)$$

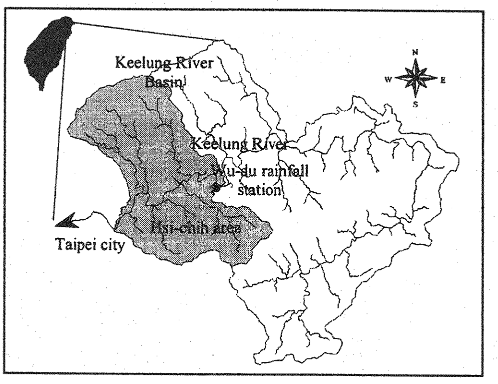


Fig. 4 General layout of Hsi-chih area

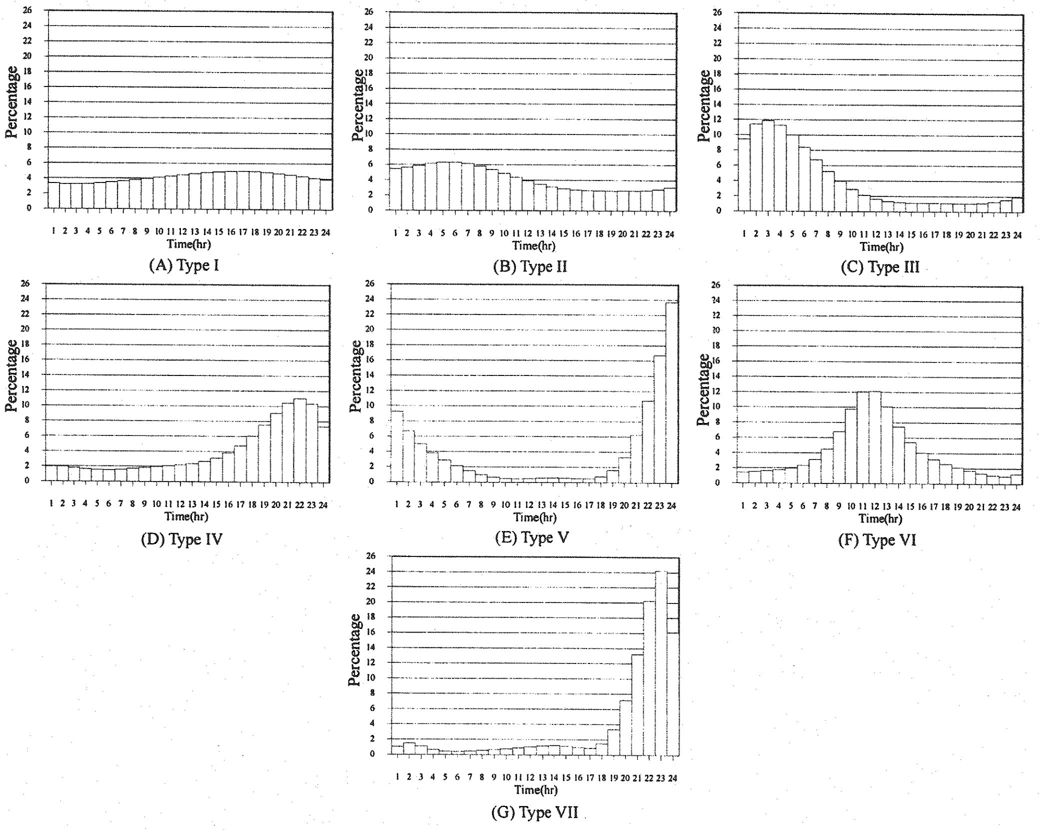


Fig. 5 Seven 24-hr rainfall distribution types in Taiwan

Since Eq. 12 is a polynomial non-linear equation, the iteration method is needed to obtain S_{PreDEV} values for selected P and $S_{PostDEV}$ values. Therefore, the required retention storage volume, which can be represented as percentage of development area, to maintain pre-development runoff volume for different degrees of development (CN) can be drawn as shown in Fig. 6. In this figure, the Y-axis represents pre-development CN values; the X-axis represents post-development CN values; the numbers in the curves represents the percentage of development area required to maintain runoff volume.

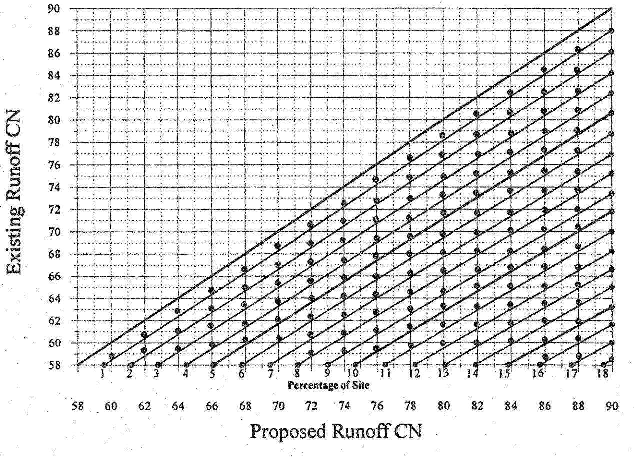


Fig. 6 Storage volume required to maintain the pre-development runoff volume using retention storage

Determine Storage Volume Required to Maintain Peak Runoff Rate Using 100% Retention and 100% Detention

Generally speaking, CN values are about 90 in most commercial and residential areas and about 70 for grassland and dirt streets and roads. Once the CN values for post-development are selected, HEC-1 package is used to calculate the retention and detention storage required for various flood peak reductions under different degrees of land development.

(1) Setting up storage volume curves for retention facilities for various flood peak reduction rates

Storage volumes required for retention facilities for various flood peak reduction rates can be obtained using HEC-1 package. Three different CN values were used and their results are shown in Fig. 7. The curve shows that as the flood peak reduction rate declines, the needed design capacity decreases accordingly. In order to facilitate the accuracy of results, the third power polynomial function as the regression design curve recommended by Soil Conservation Service (U.S. Department of Agriculture (7)) was obtained as Eq. 13, which has the coefficient of determination approaching 0.99. The estimated values from the equation have less than 5 % margin of error between calculated values for the same flood peak reduction rate. Also, the figure shows that land use has minute impact on the design curve.

$$R_{100}/Vr = 1.087-1.139(Qo/Qi)+1.272(Qo/Qi)^2-0.766(Qo/Qi)^3 \quad (13)$$

where Vr = post-development runoff volume; Qo = peak outflow discharge rate; and Qi = peak inflow discharge rate.

(2) Setting up storage volume curves for detention facilities for various flood peak reduction rate

For detention facilities simulation, a rectangular opening two meters in width was assumed. Therefore, storage volume curves for detention facilities for various flood peak reduction rates were obtained as Fig. 7 shows. The curve also shows that as the flood peak reduction rate declines, the required capacity decreases accordingly. The regression function is shown in Eq. 14 with the coefficient of determination approaching 0.99. From Fig. 7, it can be observed that for the specific flood reduction rate, the land use seems to have no significant impact on the curve. It also reveals that the volume required to maintain the peak runoff rate using detention is mush less than that of retention. The difference between detention facilities and retention facilities becomes smaller as the flood peak reduction rate is getting larger.

$D_{100}/Vr = 0.984 - 1.540(Qo/Qi) + 1.587(Qo/Qi)^2 - 0.953(Qo/Qi)^3$ (14)

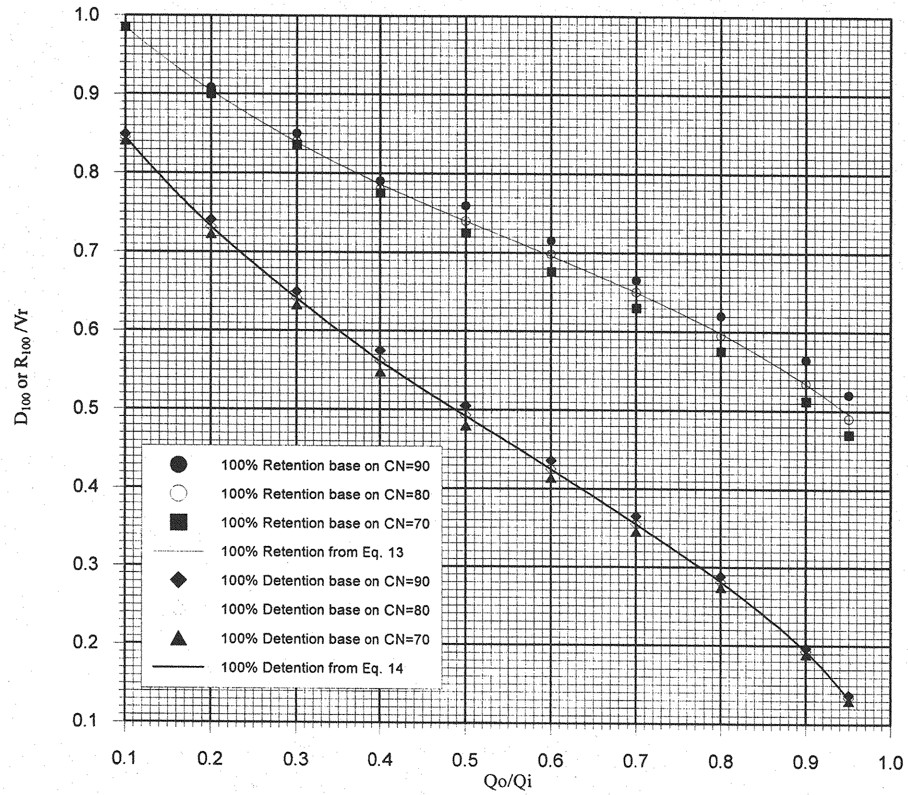


Fig. 7 Comparison of retention of storage volumes required to maintain peak runoff rate using retention and detention

(3) Design curve to maintain peak stormwater runoff rate using 100 % retention and 100 % detention for land development

For various flood peak reduction rate, the required storage capacity for detention and retention facilities can be found through Eqs. 13 and 14. However, for more convenient and practical usage, the required capacity should be linked to pre- and post-development which are usually represented by CN values.

Hence, in this study, numerous trial-and-error tests were conducted using HEC-1 package combined with Eqs. 8, 9, 13 and 14 to calculate the percentage of development area required to install the retention and detention facilities whose capacities were equal to required storage capacity calculated by Eqs. 13 and 14. These results are shown in Figs. 8 and 9. In both Figures, the Y-axis represents pre-development condition and X-axis represents post-development condition. The percentage of site represents the proportion of development area needed to install storage capacity to maintain pre-development peak discharge. From the figures, it can be deduced that for the specific flood peak reduction rate, the storage capacity required for retention facilities is larger than that of detention facilities.

APPLICATION

To demonstrate the application of series of design charts developed in the previous section, the following example is used. For given: Storm event = 314 mm; Ponding depth = 0.634 m; Existing CN = 75; Proposed CN =90.

Step 1: Determine storage volume required to maintain pre-development volume using retention storage

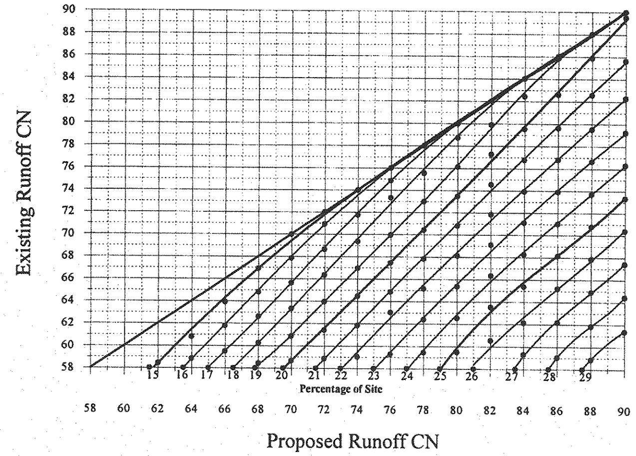


Fig. 8 Storage volume required to maintain the pre-development peak runoff rate using 100% retention

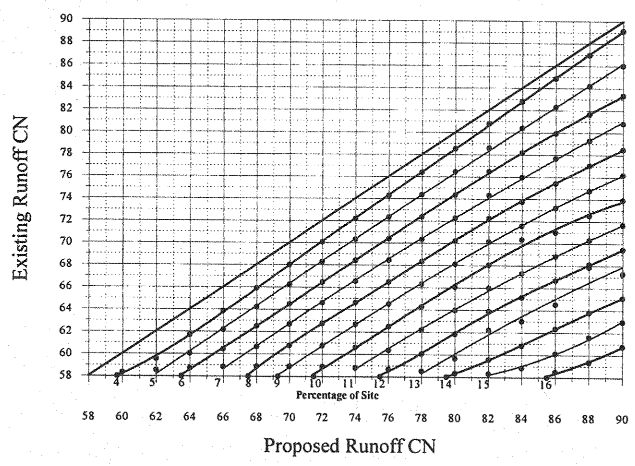


Fig. 9 Storage volume required to maintain the pre-development peak runoff rate using 100% detention

From Fig. 6, for maintaining the pre-development runoff volume, the percentage of development area needs to install retention storage is 8.1%.

Step 2: Determine storage volume required to maintain peak runoff rate using 100 % retention

From Fig. 8, for maintaining the pre-development peak runoff, the percentage of development area needs to install retention storage is 24.4%.

Step 3: Determine whether additional detention storage is required to maintain the pre-development peak runoff rate

Because the storage volume required to maintain the runoff volume is less than the storage volume required to maintain the pre-development peak runoff rate using 100 % retention, additional detention storage is required.

Step 4: Determine storage volume required to maintain peak runoff rate using 100 % detention from Fig. 9

From Fig. 9, to maintain the pre-development peak runoff, the percentage of development area needed to install detention storage is 9.5%.

Step 5: Solve for ratio of retention storage to total storage

When the percentage of site area for peak control exceeds that for volume control as determined in Step 2, a hybrid approach must be used. Therefore, x value can be obtained by solving eq. 6 and is equal to 48.4%.

Step 6: Solve for the total area to maintain both the pre-development peak runoff rate and volume

$V_{hybrid} = 8.1 \times (100 \div 48.4) = 16.7\%$

Step 7: Determine storage volume required to maintain peak runoff rate using additional detention

The difference between 16.7% and 8.1% is the additional detention area needed to maintain peak discharge. Hence, for maintaining the pre-development runoff volume and peak, we have to install retention and additional detention storage capacity with a depth of 0.634m, in which the total area should be 8.1% and 8.6% of the development area, respectively.

CONCLUSIONS

Since surface peak runoff rate and runoff volume are involved in land development, the conventional stormwater management is no longer sufficient. Stormwater management planning based on the principle of peak runoff rate completely alters the watershed hydrology and can no longer be applied straightforwardly. Furthermore, conventional stormwater management that does not change the total volume and frequency of discharge is deficient to maintain pre-development hydrologic functions.

In this paper, distributed small-scale stormwater control systems which employ small scale and distributed management practices to achieve pre-development peak runoff rate and runoff volume is considered. To interpret the hydrologic response of land use changes and site development practices, examination of a runoff hydrograph components are essential for developing successful stormwater management programs. These fundamental factors affect surface water hydrology. To implement this concept on a broad scale, analysis tools should take into account site-specific factors that influence performance. Two types of commonly used runoff estimation methods are discussed. The SCS method is selected for its widespread use and available soils database.

The hydrologic analysis of distributed small-scale stormwater control systems is a sequential decision-making process that can be illustrated by the flow chart shown in Fig. 4. Several iterations may occur within each step based on the use of the SCS TR-55 and HEC-1 hydrologic model until the appropriate approach to reduce stormwater impacts is determined. Supporting design charts have been developed to determine the amount of storage (retention and detention) required to maintain the existing volume and peak runoff rates to satisfy typical storm (Type VI) management requirements at Wu-du areas for daily rainfall with 5 years of return period. Planners can easily estimate the required retention and/or detention design capacity under a specific stormwater mitigation target. A representative example shows that if distributed small-scale stormwater control systems are considered, storage capacity required for detention is much less than that of conventional system.

The purpose of this study has been to propose systematic and scientifically sound procedures of stormwater management for land development in controlling peak runoff rate and runoff volume. In doing so, it is hoped that, through the use of the proposed procedures and the likes, much of the confusion around the planning of stormwater management for land development can be cleared up.

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APPENDIX-NOTATION

The following symbols are used in this paper:

AD	= additional detention volume required to maintain pre-development runoff peak;
A_{dmax}	= percentage of site area for facilities at d_{max};
CN	= curve number;
$CN_{PostDEV}$	= post-development CN values;
CN_{PreDEV}	= pre-development CN values;
d_{max}	= the maximum allowable design depth;
D_{100}	= storage volume required to maintain pre-development peak runoff rate using 100% detention;
DA	= development area;
f	= soil minimum infiltration rate;
loss	= percentage of the storage volume infiltrated and/or reduced by evaporation or transpiration;
P	= the depth of design storm;
P_e	= direct runoff;
Qi	= peak inflow discharge rate;
Qo	= peak outflow discharge rate;
R_{100}	= storage volume required to maintain pre-development peak runoff rate using 100% retention;
RS	= retention volume (RS) for maintaining pre-development runoff volume;
S	= the potential maximum retention;
$S_{PostDEV}$	= post-development potential maximum retention;
S_{PreDEV}	= pre-development potential maximum retention;
T_p	= ponding or storage time;
V_{hybrid}	= the total storage volume of hybrid area site;
Vr	= post-development runoff volume; and
x	= percentage of of retention storage to total storage.

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