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Hydrological Design of Recharge Structures of Urban Area

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Abstract This study deals in brief with the important aspects of rainfall measurement of short duration and its analysis for use in planning and design of roof water harvesting system. Rainwater harvesting and artificial recharge techniques can be proper hydrological interventions and better management practices to restore pre-developed or original hydrological conditions in an urbanized watershed. The procedure can be applied to other urban areas, in similar setup, to plan and design suitable infiltration structure as part of any artificial recharge scheme to possibly restore pre-developed hydrological conditions of the watershed. The observation of one minute duration rainfall data using a digital rain gauge is unique in this study. The observed rainfall data over 120 events for 5 years from 2011 and 2016is processed to derive 5, 10, 15, 30 and 60 minute rainfall and its intensity. Sub-hourly Intensity-Duration-Frequency (IDF) relationship is established by statistical analysis of the sub-hourly data observed and Extreme Value Type I or EV I frequency distribution using 30 years of maximum hourly rainfall of Bhopal city in Madhya Pradesh, India. Also, by monitoring short duration rainfall using digital rain gauges at more locations, refinements to IDF relationship for sub-hourly rainfall can be made. The sizes for recharge structures like infiltration trench and pond or basin can be designed from the procedure outlined in this study. Thus stored or diverted runoff which is input to such recharge structure can help rise groundwater table if allowed or detained for sufficient time to get infiltrated through the soils to the groundwater reservoir.

Keywords Hydrological interventions, Intensity-Duration-Frequency, artificial recharge and groundwater

Introduction

In this study a methodology to design the sizes of artificial recharge structures like infiltration trench and infiltration pond is presented. This procedure, based on the rooftop runoff storage linked to in-situ infiltration from a recharge structure, is required to face the impacts of modification to the hydrology in any watershed due to change in land use or stage of its urbanization. By adopting a conceptual model of Akan [1] certain relationship is developed to estimate the size of artificial recharge structures and same is demonstrated to plan proper interventions to restore groundwater levels in depleted aquifers of urban watershed in Bhopal. According to Ineson [2], the deciding factor in selection of a recharge structure is the ability of the aquifer below to store recharging water temporarily and to permit groundwater movement subsequently at acceptable rates and over adequate retention times. Also, efficiency of abstraction works to recover the recharge water is an important factor that influences the selection of appropriate rainwater harvesting structure. In this study such a procedure for proper planning of rainwater harvesting and hydrological design of infiltration structures in urban watersheds is presented. This helps in estimating the sizes of artificial recharge structures like infiltration trench and infiltration basin. The developed relationship is applied for a major urban watershed of Budampeta drain in the city and areas and sizes of artificial recharge structures necessary are suggested for maintaining or restoring normal hydrological conditions for the stage of complete urbanization in the watershed.

Study Area

Bhopal is popularly known as the city of Lakes. Bhopal gets this distinction because of a large number of lakes, tanks and ponds in the city shown in Figure 1. The city is relatively away from a dependable perennial lotic water source; hence the administrators had to construct ponds and reservoirs in order to cater the needs of the city. Presently the city occupies a geographical area of about 285.88 km^2 and According to the 2011 census, the population of the Bhopal city (the area under Bhopal Municipal Corporation) is 1,798,218, with 936,168 males and 862,050 females.

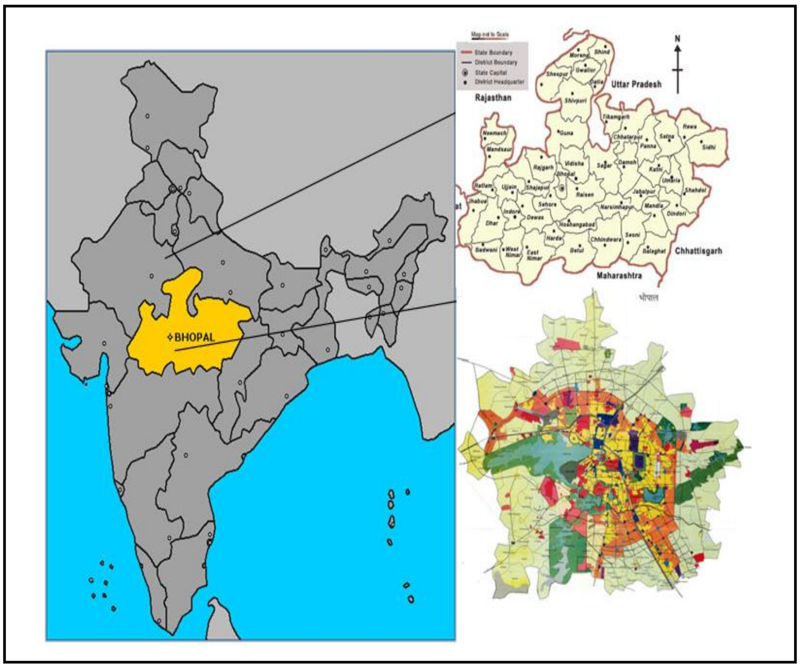

Figure 1: Inventorization of electronic waste from selected target area of Bhopal city

Design of Artificial Recharge Structures

A roof water harvesting system comprises of a rooftop as a catchment; a reservoir to store collected water and a delivery setup to meet the demands. The storage structure can be a surface reservoir or sub surface or an underlying aquifer media as groundwater reservoir. In an urban watershed, for restoration of groundwater in its aquifer system to its natural condition or pre-urbanization condition, the sizes of recharge structures like trenches or ponds like its surface area and depth have to be properly fixed. This is also called sizing of the recharge or infiltration structure. This exercise of proper design for sizing of recharge structure to dispose of the excess runoff is always a challenge. In this study, a procedure towards solving this challenge is suggested by analyzing the interaction of surface water and groundwater processes. To start with, hydrologic budget of the plot area or the micro urban watershed area over a rainy day is to be evaluated.

Sizing of infiltration structures

The methodology of design of a recharge trench and recharge pond or tank or basin is similar. Only difference is that the water-holding capacity of a recharge trench is less than its gross volume because it is filled with porous material. A factor for the density of the media or void ratio has to be applied in the model equation. The void ratio of the filler material varies with the kind of material used, but for commonly used materials like brickbats, pebbles and gravel, a void ratio of 0.5 may be assumed. In designing a recharge trench, the length of the trench is an important factor. Once the required capacity is calculated, length can be calculated by considering a fixed depth and width.

To design the recharge structure, peak intensity of rainfall and its duration have to be considered to assess the total volume of water which shall be available during this period. This is most important as 80% of rainfall occurs in 3 to 5 rainstorms. The total volume of runoff likely to be generated during peak intensity can be estimated by applying a run off coefficient. The capacity of recharge tank is designed to retain runoff from at least 15 minutes rainfall of peak intensity. For example for Delhi, peak hourly rainfall is 90 mm based on 25 year frequency and 15 minutes peak rainfall is 22.5 mm according to CGWB norms [3]. For Bhopal, short duration rainfall analysis for its intensity-duration-frequency is carried out and a relationship is developed.

A widely accepted design standard or procedure for infiltration practices is difficult to find. Akan [1] presented a design aid based on surface water groundwater interaction of runoff and unsaturated flow process for sizing infiltration structures. This procedure is based on the hydrological storage equation for an infiltration structure coupled with infiltration equation. For the filling process, the two equations are solved simultaneously using a numerical method, and the results are presented in a non dimensional parametric charts. These charts are useful to determine the maximum water depth in an infiltration structure. This design aid and charts are followed in this study for design of artificial recharge structure like infiltration trench and basin and in developing relationships for planning the same in Bhopal city. According to Schueler [4], such capture volume for infiltration trenches can be calculated as the volume of 12.7 mm or 0.5" of runoff over the impervious portion of the contributing area. In this study, the infiltration structure is designed for a maximum rainfall of 20 mm, which is the average rainfall over a rainy day at Bhopal.

Modelling Infiltration Structures

Bouwer [5] explained in detail the role of hydrogeology and engineering aspects of artificial recharge of groundwater. The aquifer should be sufficiently transmissive and excessive buildup of groundwater mounds is to be avoided. To systematically design an artificial recharge system, infiltration rates of the soil need to be determined and the unsaturated zone between land surface and aquifer must be checked for adequate permeability and absence of polluted areas.

The process of flow through unsaturated zone as physically conceptualized by Green and Ampt [6] was verified in the past in various studies [7]. According to Morel-Seytoux and Khanji [8], the parameters of the Green and Ampt model have a precise physical meaning, unlike other available simple infiltration models. Also, the model is well documented by Rawls *et al* [9]. Akan [1] presented a technical note based on rational hydrologic principles and using the Green and Ampt infiltration model the process of rainfall recharge through a given infiltration structure. He developed charts useful for sizing of infiltration structure, i.e., to determine the maximum water depth and the storage time in infiltration structures.

Infiltration trench

Infiltration pit or trench is a popular artificial recharge structure being built at residential plots and public places in urban watershed. Its construction and maintenance is simple and is discussed in section 1.4.1 of chapter I. Apart from hydrological data, adopting appropriate soil characteristics of the land surface and back fill material is important. A wetting zone will develop at the bottom of the infiltration structure and increases in depth as the water percolating from the structure fills into this zone without any loss. Below the wetted zone is a dry zone where the initial soil moisture content is maintained. The dry zone is assumed to have unlimited depth. Hence, the water table or the bedrock is deep enough not to interfere with the infiltration process.

Filling Process

The filling process begins when the runoff first reaches the trench. Vertical infiltration takes place primarily through the bottom of the trench during the filling process. Lateral infiltration through the sides of the trench is usually neglected since the hydraulic gradients in the vertical direction dominate the process. The equation of Green and Ampt [6] to express the rate of infiltration is as below.

$$n_A \frac{dh}{dt} = q - K_s \left(\frac{Z + h + P_f}{Z} \right) \tag{1}$$

Here, h is depth of water in the trench, n_A is porosity of the aggregate fill material of the trench, q is rate of roof harvest due to the design storm including rainfall directly over the trench, intercepted per unit horizontal area of the trench, t is time, Ks is saturated permeability of the underlying soil, P_f is characteristic suction head of the soil and Z is depth of the wetted zone below the bottom of the trench. The second term on the right-hand side of

Eq. 1 expresses the rate of infiltration assuming the pressure distribution within the trench is hydrostatic. This assumption neglects the energy losses due to the vertical movement of the water within the trench. However, the assumption is justified since the aggregate fill material within the trench is usually much more permeable than the underlying soil whose porosity is n and initial moisture content is S_i. The change in the depth of the wetted zone is evaluated using

$$n(1-S_i)\frac{dZ}{dt}=K_s\frac{Z+h+P_f}{Z} \quad (2)$$

Many a time, the filling process can end and the emptying process can begin while the trench is still receiving runoff if the rate of infiltration from the trench exceeds the inflow rate. But, in case of roofwater harvesting system, the runoff rates are normally much higher than the infiltration rates during 'design storm' event. Therefore, it can be reasonably assumed that the filling process will continue until the entire capture runoff has entered the trench. According to the Maryland Dept. of Resources (1984) definition for the capture runoff, the filling is assumed to continue until up to filling time i.e., t is T_f. The runoff captured during the filling process is stored partly in the trench and partly within the wetted zone of the soil. Therefore, assuming the water and the porous media both to be incompressible, the law of conservation of mass requires

$$R=n_A h_0+n(1-S_i)Z_0 \quad (3)$$

Where, R is capture volume or design runoff volume per unit horizontal surface area of the trench including the rain falling directly on the trench; h_0 is the depth of water in the trench at t is T_f; and Z_0 is thickness of the saturated zone or wetted zone at t is T_f. Rearranging Eq. 3 as

$$\frac{Z_0}{R}=\frac{1}{n(1-S_i)}\left(1-n_A\frac{h_0}{R}\right) \quad (4)$$

Additional relationships can be found between h_0 , Z_0 , R, and the soil and trench characteristics by integrating Eqs. 1 and 2 over the filling time T_f. To generalize the procedure Akan [1] integrated the differential forms of above equation numerically in terms of various dimensionless parameters and presented a chart for fixing the sizes of infiltration trench as shown in Fig. 2 and 3. Sensitivity analysis of parameters indicated that the chart is suitable for practical uses, as the error was within 5%.

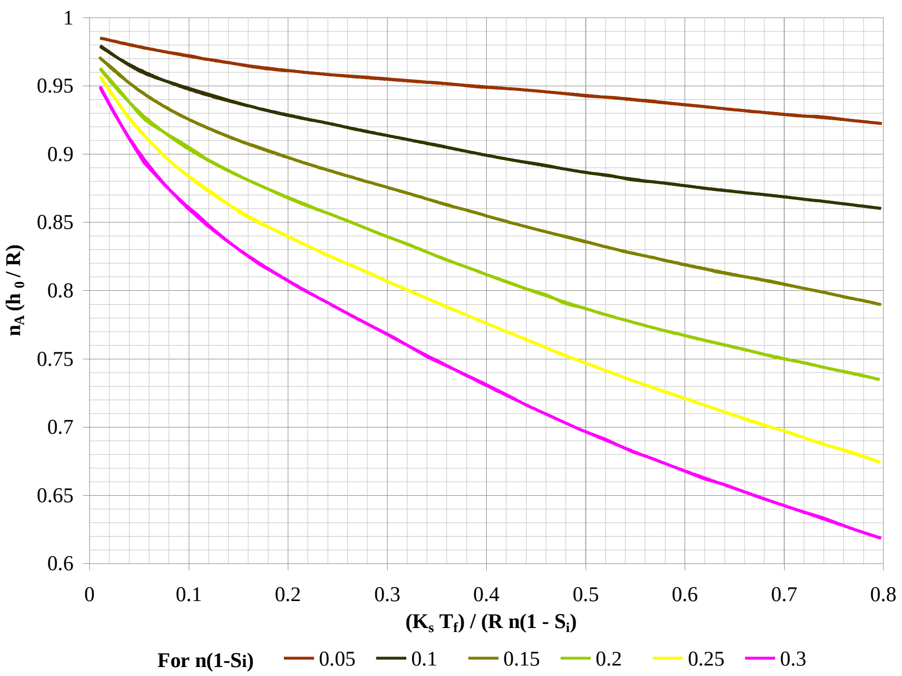

Figure 2: Chart for fixing the sizes of infiltration or recharge trench

Sizing of infiltration structures for Bhopal

The procedure as proposed by Akan [1] and discussed in detail in previous section is adopted for fixing the sizes of infiltration structures as this method is based on rational hydrologic principles of surface water and groundwater interaction. The sizes of infiltration structure, i.e., the maximum water depth and the storage time in infiltration structures can be conveniently estimated from this technique. The application of this procedure for design of infiltration structure in alluvial aquifers and planning artificial recharge in an urban watershed.

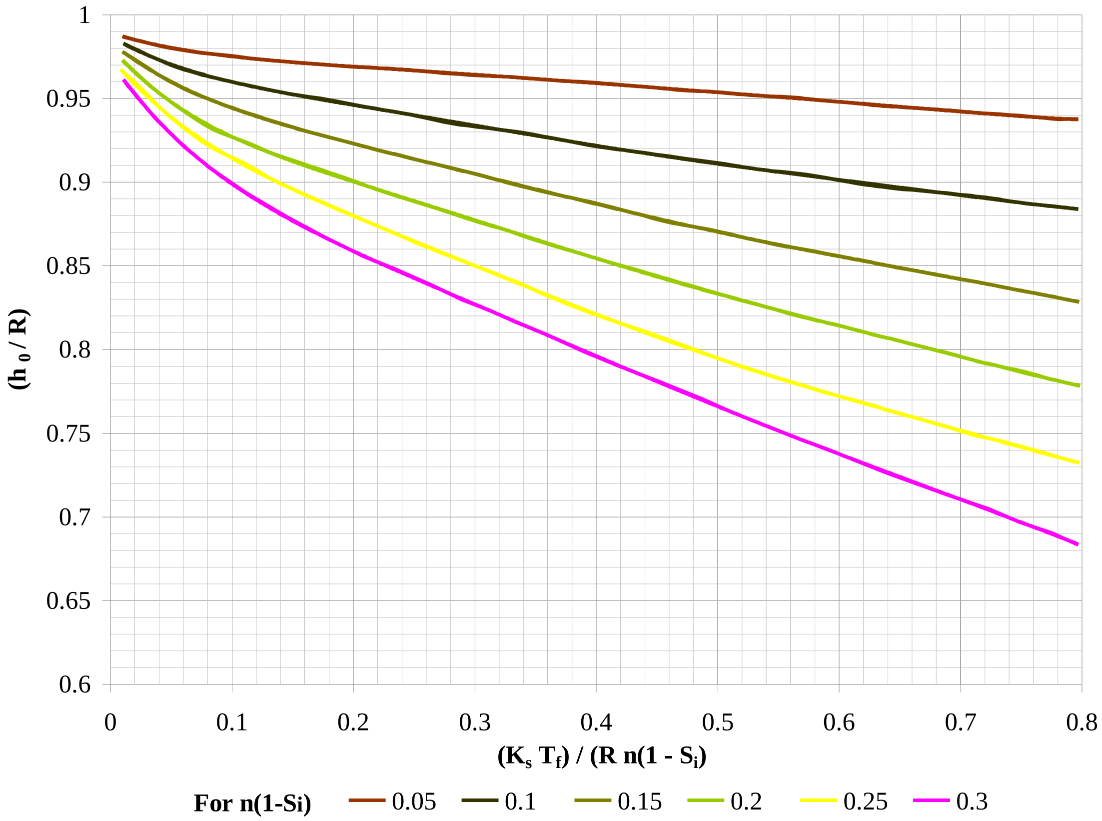

Figure 3: Chart for fixing the sizes of infiltration or recharge basin

As the land value is very high in urban areas the proportion of surface area left for artificial recharge structure should be as less as possible. But, at the same time the structure should have sufficient capacity to store runoff harvest. In coastal alluvial area, such as Bhopal, where groundwater table is not deep, the depth of infiltration structure needed to be kept well above water table. Hence, in this study the depth of infiltration trench and basin are estimated for areas varying from 2% to 4% for trench and 1% to 3% of given plot area of 500 m^2 for trench and basin as listed in Table 1. These can be adopted based on groundwater table conditions of the layout and as per the restriction of depth of structures and land area available, a suitable surface area can be chosen while finalizing the size of the infiltration structure.

Table 1: Surface areas considered for recharge structures

Infiltration structure type by surface area size	I	II	III	IV
Trench area in m^2	10	12	15	20
Basin or Pond area in m^2	5	8	10	15

The water budget was undertaken for the proposed urban watershed in layout of 2500 sq. m as discussed in earlier chapters. Accordingly when the layout is completely urbanized, a runoff harvest of 9.5 m^3 of for each plot of 500 m^2 resulting from a average rainy day rainfall of 20 mm need to be disposed of by artificial recharge structures. The soil water properties of in-situ soil for coastal alluvium of the urban layout studies are essential for the sizing of structure in this procedure. The values considered are shown in Table 2. Assuming the stone fill has a porosity, 'n_A' of 0.40 and most of the runoff that can actually occur over a rainy event has a filling time

'T_f' of 120 minutes or 2 hours, the maximum water depth in the proposed recharge structure and the storage time are estimated as explained below.

Table 2: Soil water properties of in-situ soil and fill material

Soil property	Value
Porosity of fill material nA	0.4
Saturated permeability of Insitu soil Ks in m/hour	0.02
Characteristic suction head of insitu soil Pf in m	0.11
Porosity of insitu soil n	0.42
Initial water saturation of insitu soil Si	0.52
Estimated filling time T_f in hours	2

Conclusions

There is possibility that the roofwater harvest more than 9.5 m^3 occurring during intense or prolonged event will over flow to storm water drainage. Large infiltration pond or basin is to be planned by local urban planning authority to accommodate such surplus from plot level before it inundates any low lying area or discharges into natural drainage or water bodies for proper harvesting of excess runoff. It is recommended that while planning recharge basins or ponds, these can be integrated, wherever possible, with flood detention ponds if any being planned. This methodology can be adopted for planning and designing artificial recharge measures in urban watersheds not only for Bhopal city but also similar hydro-meteorological and geo-morphological units elsewhere in the region.

Studies may be extended to develop simple procedure for design of recharge shafts, recharge tube wells etc., needed for urban watershed located in upland areas. Though these results can be adopted reasonably well for undertaking preliminary studies to plan and design artificial recharge measures as hydrological interventions, three dimensional groundwater flow modeling may be undertaken in critical areas.

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