

# **Groundwater Recharge Systems for Stormwater Disposal**

*Dissertation submitted in partial fulfillment of the requirement*

*for the award of the degree of*

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*in*

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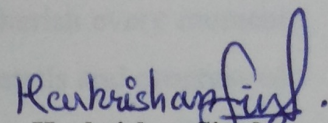
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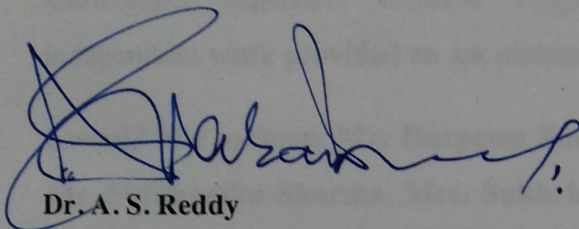
This is certified that the thesis entitled "Groundwater Recharge Systems for Stormwater Disposal" is an authentic record of my own work carried out as requirements for the award of the degree of M. Tech. (Environmental Science & Technology) at Thapar University, Patiala, under the guidance of **Dr. A. S. Reddy** (Associate Professor, SEE) during July 2012 to July 2013.

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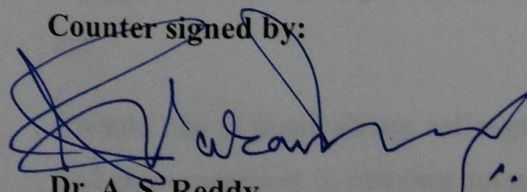
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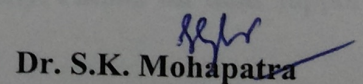
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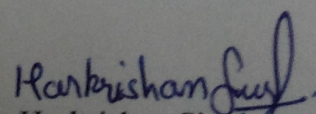
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## **ABSTRACT**

Stormwater has many health and environmental problems, and stormwater management is a major challenge in almost all developing and developed countries. Disposal of Stormwater by Groundwater Recharging is one of the multitudes of structural Best Management Practices (BMPs) developed for mitigating the adverse impacts of stormwater. Very few attempts have been made to treat and use the stormwater in groundwater recharging. Random rainfall events, existence of first flush, and highly variable volumes and pollution loads, make treatment and use of the stormwater in ground water recharging a real challenge. In the present study, the technical aspect of design of groundwater recharge system for stormwater disposal has been taken up. The study involved development of protocol for the design of recharge systems for disposing the pretreated stormwater of two selected sub-watersheds, one urban and the other rural.

**Keywords:** stormwater/stormwater-runoff management, groundwater recharge, artificial recharge, recharge system.

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## ABBREVIATIONS

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BMP	Best Management Practices
BOD	Biological Oxygen Demand
cm	centimeter
COD	Chemical Oxygen Demand
ft	feet
g/m <sup>2</sup>	gram per square meter
hr	hour
kg/m <sup>3</sup>	kilogram per cubic meter
L/T	Dimension of length per unit time
L <sup>2</sup> /T	Dimension of square length (area) per unit time
L <sup>3</sup>	Dimension of cubic length (volume)
L <sup>3</sup> /T	Dimension of cubic length (volume) per unit time
m	meter
m/hr	meter per hour
m/sec <sup>2</sup>	meter per square second
m <sup>3</sup> /hr	cubic meter per hour
mg/l	milligram per liter
mhm	million hectare meter
min	minute
ml	milliliter
mm	millimeter
NO <sub>2</sub> <sup>-</sup>	nitrite
NO <sub>3</sub> <sup>-</sup>	nitrate
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
µm	micro meter
US EPA	United States Environmental Protection Agency

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# Chapter 1

## INTRODUCTION

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Indian subcontinent having an area of 329 million hectares has a wide spectrum of physiographic, hydrogeological and hydrometeorological features. The rainfall varies from 10 cm in western Rajasthan to more than 1100 cm in Chirapunji district of Meghalaya. The average annual precipitation estimated over the country is 1170 mm of which 75 percent is received between June and September, 10 to 11 percent between October and December, 3 to 4 percent during January and December and 10 to 11 percent as pre-monsoon rainfall. The annual precipitation of the country is 400 million hectare metres (mhm). Nearly 70 mhm is lost as evaporation, 215 mhm infiltrates naturally and 115 mhm as stormwater run-off (Raju, 1998).

The management of this stormwater run-off is posing many challenges in India as well as other developing countries. Consequences of its neglect are severe. Inadequate management can pollute the environment and squander the limited fresh water resources. Flooding and environmental health problems relating to poor drainage are widespread.

Rapid expansion and associated increase of impermeable areas, together with the tropical rainfall conditions, increase both frequency and intensity of floods. Disturbance of natural drainage and conversion of low-lying areas into colonies are making the situation further worst. Lack of planning and delays in the construction of drainage infrastructure (common in cities of developing countries) can aggravate the problems.

Stormwater can adversely affect water quality of the receiving water bodies by changing both their chemistry and hydrology. Increased imperviousness increases runoff volume and peak flows. These in turn cause floods and increase stream erosion. The Nationwide Urban Runoff Program (NURP) study conducted by the US EPA (Water Planning Division, USEPA, 1983) indicated presence of high levels of a wide spectrum of pollutants in storm water, specially from 'urban hot spots', such as parking lots, heavily traveled roads, car washes, fertilized lawns, etc.

Depleting and deteriorating groundwater resources (rapidly declining ground water table and deteriorating ground water quality) has been another serious problem. Through expanding the impervious areas, recharging of groundwater is minimized. Over exploitation of ground water for municipal use is adversely affecting both quantity and quality of groundwater resources. The situation is rapidly worsening with the increasing urbanization and increasing water demands. Augmentation of the available groundwater resources through rainwater harvesting and artificial recharge can prove an effective strategy. The current widely used and much known roof top rainwater harvesting, no doubt, augments the urban groundwater resources, but to a limited extent, through both recharging the groundwater and minimizing pumping out of the groundwater for municipal use. For making the much-needed difference, stormwater may need collection and use for recharging the groundwater. Cost effective methods of groundwater recharge are key to sustainable groundwater management in both developing and developed countries (Jha et. al., 2008). This can tackle the floods problem and avoid pollution of the environment, specially the receiving water bodies. However, stormwater is heavily polluted and cannot be used for groundwater recharging without prior treatment.

Over the last 30 years, quite a few advances have been seen around the world in the area of Stormwater Management (Daniel, 2008). To mitigate the adverse impacts of stormwater on receiving water bodies, various structural Best Management Practices (BMPs), such as, detention and infiltration ponds, vegetative filter strips, infiltration trenches, biofiltration swales, bioretention cells, etc., have been developed (Anderson, 2007). Field and laboratory studies have been undertaken by several researchers to determine pollutant removal by many of these structural BMPs (Revitt et al., 2008).

The need of the hour is to develop a design protocol to aid in the installation and operation of recharge systems using stormwater to recharge groundwater. There have been numerous attempts at recharging the groundwater artificially by collection of stormwater, of which most involve intensive ground condition testing to design recharge structure that are apt to the specific area in which it is being installed. This may not prove to be a very good strategy, as it does not provide prior information of the feasibility of the project taken in hand or any beforehand estimates of the

capabilities of the recharge structure being designed.

### **1.1 Objective of work**

The aim of this study is

1. To understand the process of artificial groundwater recharge; the systems being used for recharging
2. To develop a design protocol for recharge systems in urban and rural areas
3. To use the developed protocol for select case studies in urban and rural area

### **1.2 Scope of work**

1. Literature had been reviewed from peer journals (groundwater recharge related), manuals, books, case studies, reports and internet sources.
2. Background information needed for the design was collected from Water Supply Department, Patiala and Water Supply Department, Barnala.
3. Design protocol was developed using the literature and background information available.
4. The design protocol was used for design of recharge systems for select case studies (urban and rural).

### **1.3 Significance of work**

1. Most of the design protocols available depend on installing a pilot scale system first and then determining the design of the recharge system to be installed on the basis of the results obtained from the pilot scale system.
2. The design protocols given in this work are based on limited information that can be acquired from Water Supply Department of respective district or from local driller of boreholes hence, it makes the design procedure much easier than any protocol available.

### **1.4 Outline of work**

1. Chapter 2 contains literature review on various aspects that are required to be considered in the design of recharge systems.
2. Chapter 3 describes the methodology adopted in the development of design protocol for the recharge systems.

3. Chapter 4 gives a brief overview on artificial recharge, recharge systems available, studies that should be undertaken for design purpose, pretreatment of stormwater and problems faced during operation of recharge systems.
4. Chapter 5 contains the design protocol for the development of recharge systems and results of its application to design recharge systems for select case studies of urban and rural area.
5. Chapter 6 contains the overall conclusion of this study.

There has been a number of studies conducted in the area of artificial recharge of groundwater by stormwater majority of which are dependent on actual ground conditions testing and use of pilot scale plants to determine the efficacy of the system to be installed. It is more of a hit and trial method and only few studies have incorporated the actual design procedure to be followed before a full-scale or pilot scale system is installed.

The literature survey of the present study is divided into the following categories for in-depth study of various aspects involved in the design of recharge systems to artificially recharge groundwater by stormwater.

1. Stormwater and their characteristics
2. Stormwater treatment alternatives to meet quality requirements
3. Groundwater recharge technologies
4. Background information
5. Design, operation and control of groundwater recharge systems

### **2.1 Stormwater and their characteristics**

Maestre et al., (2005) gave the maximum concentration of various parameters of stormwater in areas with different land use viz. Residential (RE), Commercial (CO), Industrial (ID) and Open Area (OP).

**Table 1:** Constituents of stormwater and their concentration

S.No.	Constituent	Maximum Concentration			
		RE	CO	ID	OP
1	Hardness (mg/l)	401	356	888	270
2	Oil and Grease (mg/l)	2980	359	11000	4
3	TDS (mg/l)	1700	3860	11200	542
4	TSS (mg/l)	2426	2385	2490	980
5	BOD (mg/l)	350	150	6920	20
6	COD (mg/l)	620	635	1260	476
7	Fecal Coliform (Colonies/100 ml)	$5.23 \times 10^6$	$6.1 \times 10^5$	$2.5 \times 10^6$	$6.3 \times 10^4$
8	Ammonia (mg/l)	6	8	10	2
9	NO <sub>2</sub> <sup>-</sup> + NO <sub>3</sub> <sup>-</sup> (mg/l)	8.21	8.4	3.33	36
10	TKN (mg/l)	36	15	25	5
11	Total Phosphorous (mg/l)	7	3	8	15

Source: (Maestre et al., 2005)

\*RE: Residential Area, CO: Commercial Area, ID: Industrial Area, OP: Open Area

Winiarski et al., (2006) studied the effects of urban stormwater on the soil of an infiltration/ holding basin. The bio-physicochemical impacts of stormwater from an industrial watershed on the soil (upto 4 m depth in the unsaturated zone) were studied. Several measurements (pH, organic matter, particle size, heavy metals content, and heterotrophic viable bacterial counts) for three vertical soil profiles were carried out. High concentrations of heavy metals and significant variations in pH and silt to a depth of 1.5 m were observed. The concentrations decreased as a function of distance from the stormwater discharge pipe. Changes in the bacterial population were also observed.

Arora and Reddy (2012) have reported the characteristic of stormwater at various sites in Patiala city, Punjab. This was used as the basis for determining the characteristic of stormwater for treatment.

Research work is being carried out in Thapar University, Patiala on the quantification of stormwater from various sub-watersheds of Patiala and sub-watersheds of Chhapa village (distt. Barnala).

## 2.2 Stormwater treatment alternatives to meet quality requirement

Vermont Agency of Natural Resources (2002) provides regulatory requirements for the management of stormwater and technical guidance for the design of stormwater

treatment practices. It sets forth required stormwater treatment standards, and design criteria for water quality, groundwater recharge, channel protection, overbank flood protection and extreme flood control. Besides these, it comprehends the stormwater treatment practices (which can be used either alone or in combination) acceptable to meet the treatment standards.

Hatt et al., (2006) reviewed Australian stormwater treatment and recycling practices with focus primarily on the recycling of general urban runoff (runoff generated from all urban surfaces) for non-potable purposes. The author indicated a clear need for the development of innovative techniques for the collection, treatment and storage of stormwater.

Lim et al., (1999) studied urban stormwater collection for portable use being practiced in Singapore. Almost half of the city's total land area has been utilized as water catchments. Public Utilities Board (PUB) of the city had embarked on a unique scheme to implement urban stormwater pond collection systems in catchments to exploit the harnessing of storm runoff from new townships and augment its limited water supplies. According to the author, the urban stormwater collection systems are feasible, through implementation of a coordinated and integrated approach to development control and land use planning, together with innovative design and effective catchments management. Close monitoring and control of pollution, through the adoption of stringent anti-pollution measures, and enforcement actions have resulted in the collection of generally good quality raw water from these urbanized catchments with very low levels of heavy metals and low coliform counts. Since then, newer urban stormwater pond collection stations have been implemented or are being planned in the northern and northwestern parts of Singapore to replace the existing stream abstraction stations.

Research work is being carried out in School of Energy and Environment, Thapar University to use cyclone removal of suspended solid from stormwater in conjunction with multistage, multigrade up-flow roughing filters as a pretreatment process to reduce both inorganic and organic suspended solids as well as biomass present in the stormwater. The concentration of suspended solids in the outlet stream is expected to

be less than 10 mg/l. The research work is not yet published.

### 2.3 Groundwater recharge technologies

Raju (1998) has described various recharge methodologies used in the artificial recharge of groundwater, which can be categorized as follows.

**Table 2:** Various groundwater recharge technologies

S.No.	Method				
1	Direct	Surface Spread Techniques	Flooding		
			Ditch & Furrow		
			Recharge Basin		
			Run-off conservation Structures	Gully Plugs	
				Bench terracing	
				Contour bund	
				Nala bund	
		Percolation tank			
		Individual well recharge			
		Stream Modification			
		Surface irrigation			
		Sub-surface Techniques	Injection Wells		
			Gravity Head Recharge Wells		
Aquifer Storage & Retrieval (ASR)					
Soil Aquifer Treatment (SAT)					
2	Indirect Methods	Induced Recharge	Pumping Wells		
			Collector Wells		
			Infiltration Gallery		
		Aquifer Modification	Bore Blasting		
			Hydrofracturing		
3	Combination Methods	Groundwater Conservation Structures	Groundwater dams		
			Fracture sealing cementation techniques (FSC)		

Source: (Raju, 1998)

Bouwer (1999) has described various groundwater recharge technologies in detail with aspects governing the selection of a particular recharge system based on

hydrogeological parameters.

Singh and Ravichandran (2011) have proposed various methods of estimation of groundwater recharge, which can be adopted to improve the ground water situation.

CGWB (2007) has given detailed description of groundwater recharge technologies with technical aspects in reference to Indian conditions.

ASCE Standard (2001) states that Flood Spreading is an efficient strategy for controlling floods and managing water shortage and water resources.

Barnett et al., (2001) has presented several case studies where aquifer storage and recharge techniques have been successful with savings in water and infrastructure costs, as well as providing environmental benefits.

Dhakad and Agrawal (2009) have showed that recharge tube wells resulted in groundwater level rise by 0.7 to 1.97 m per annum. The payback period of such system is nine months.

Jha et al., (2008) has proposed three low-cost and easy to implement recharge techniques in Japan viz. augmentation of river flow, recharge through irrigation/drainage canals, and recharge from paddy fields.

D'Oria et al., (2008) stated that the hydraulic risks and economic budget in management of small structures like small ponds or lakes are lower than those involved in traditional reservoirs. The designing requires only few parameters: the geometry of the problem, the initial lake and groundwater level and the hydraulic parameters of the aquifer and of the bottom of the lake/pond.

Flint and Ellet (2004) stated that, the optimal conditions for selection of site for artificial recharge has, high permeability, capacity for horizontal flow at the aquifer boundary, a lack of impeding layers, and a thick unsaturated zone.

## 2.4 Background information

A number of background information is required for the design of infiltration facilities. These include saturated hydraulic conductivity, storativity, specific yield etc.

Rhode Island Stormwater Design and Installation Standards Manual (2010) has presented values for minimum horizontal setback from an infiltration facility of various structures.

**Table 3:** Minimum Horizontal Setback from Infiltration Facilities

S.No.	Structure	Minimum Horizontal Setback (ft)
1	Public Drinking Water Supply Well – Drilled (rock), Driven, or Dug	200
2	Public Drinking Water Supply Well – Gravel Packed, Gravel Developed	400
3	Private Drinking Water Wells	100
4	Surface Water Drinking Water Supply Impoundment with Supply Intake	200
5	Tributaries that Discharge to the Surface Drinking Water Supply Impoundment	100
6	Coastal Features	50
7	All Other Surface Waters	50
8	Up-gradient from Natural slopes > 15%	50
9	Down-gradient from Building Structures	25
10	Up-gradient from Building Structures	50
11	Onsite Wastewater Treatment System	25

Source: (Rhode Island Stormwater Design and Installation Standards Manual, 2010)

Massmann (2003) has given the equation for calculation of saturated hydraulic conductivity based on a comparison of hydraulic conductivity estimates from air permeability tests with grain size characteristics.

$$\log_{10}(K_{sat}) = -1.57 + 1.90D_{10} + 0.015D_{60} - 0.013D_{90} - 2.08f_{fines} \quad (2.4.1)$$

where,

$D_{60}$  is grain size for which 60 percent of the sample is more fine

$D_{90}$  is grain size for which 90 percent of the sample is more fine  
 $f_{\text{fines}}$  is fraction of soil (by weight) that passes the number 200 sieve

Saturated hydraulic conductivity values for various unconsolidated sedimentary materials, sedimentary rocks and crystalline rocks are given in Table 4.

**Table 4:** Saturated hydraulic conductivity values for various materials

**Table 4a:** Saturated hydraulic conductivity values for unconsolidated sedimentary materials

<b>Unconsolidated Sedimentary Materials</b>	
<b>Material</b>	<b>Saturated hydraulic conductivity (m/sec)</b>
Gravel	$3 \times 10^{-4}$ to $3 \times 10^{-2}$
Coarse Sand	$9 \times 10^{-7}$ to $6 \times 10^{-3}$
Medium Sand	$9 \times 10^{-7}$ to $5 \times 10^{-4}$
Fine Sand	$2 \times 10^{-7}$ to $2 \times 10^{-4}$
Silt, loess	$1 \times 10^{-9}$ to $2 \times 10^{-5}$
Till	$1 \times 10^{-12}$ to $2 \times 10^{-6}$
Clay	$1 \times 10^{-11}$ to $4.7 \times 10^{-9}$
Unweathered marine clay	$8 \times 10^{-13}$ to $2 \times 10^{-9}$

**Table 4b:** Saturated hydraulic conductivity values for sedimentary materials

<b>Sedimentary Rocks</b>	
<b>Rock Type</b>	<b>Saturated hydraulic conductivity (m/sec)</b>
Karst and reef limestone	$1 \times 10^{-6}$ to $2 \times 10^{-2}$
Limestone, dolomite	$1 \times 10^{-9}$ to $6 \times 10^{-6}$
Sandstone	$3 \times 10^{-10}$ to $6 \times 10^{-6}$
Siltstone	$1 \times 10^{-11}$ to $1.4 \times 10^{-8}$
Salt	$1 \times 10^{-12}$ to $1 \times 10^{-10}$
Anhydrite	$4 \times 10^{-13}$ to $2 \times 10^{-8}$
Shale	$1 \times 10^{-13}$ to $2 \times 10^{-9}$

**Table 4c:** Saturated hydraulic conductivity values for crystalline rocks

<b>Crystalline Rocks</b>	
<b>Rock Type</b>	<b>Saturated hydraulic conductivity (m/sec)</b>
Permeable basalt	$4 \times 10^{-7}$ to $2 \times 10^{-2}$
Fractured igneous and metamorphic rock	$8 \times 10^{-9}$ to $3 \times 10^{-4}$
Weathered granite	$3.3 \times 10^{-6}$ to $5.2 \times 10^{-5}$
Weathered gabbro	$5.5 \times 10^{-7}$ to $3.8 \times 10^{-6}$
Basalt	$2 \times 10^{-11}$ to $4.2 \times 10^{-7}$
Unfractured igneous and metamorphic rock	$3 \times 10^{-14}$ to $2 \times 10^{-10}$

Source: (Domenico and Schwartz, 1990)

Todd (1980) showed that storativity of confined aquifer varies with specific storage and aquifer thickness and typically ranges from  $5 \times 10^{-5}$  to  $5 \times 10^{-3}$  and Lohman (1972) observed that storativity of an unconfined aquifer depends on specific yield and typically ranges from 0.1 to 0.3.

Bear (1979) has given a relation between specific yield and total porosity as follows

$$n = S_y + S_r \quad (2.4.2)$$

where,

$n$  is total porosity [dimensionless]

$S_y$  is specific yield [dimensionless]

$S_r$  is specific retention [dimensionless]

Specific retention is the amount of water retained by capillary forces during gravity drainage of an unconfined aquifer. Thus, specific yield, which is sometimes called effective porosity, is less than the total porosity of an unconfined aquifer (Bear, 1979).

Porosity, specific yield and specific retention values for different soils are given in Table 5. Table 6 gives representative values of specific yield for different geological materials/soils.

**Table 5:** Porosity, specific yield and specific retention for different geological material/soils

<b>Material</b>	<b>Porosity (%)</b>	<b>Specific Yield (%)</b>	<b>Specific Retention (%)</b>
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (unconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (young)	11	8	3

Source: (Heath, 1983)

**Table 6:** Specific yield for different geological materials/soils

<b>Material</b>	<b>Specific Yield (%)</b>
Gravel, coarse	21
Gravel, medium	24
Gravel, fine	28
Sand, coarse	30
Sand, medium	32
Sand, fine	33
Silt	20
Clay	6
Sandstone, fine grained	21
Sandstone, medium grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44
Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

Source: (Morris and Johnson 1967)

Batchelor (1967) gave the equation for capillary rise as follows

$$h_c = \frac{2T \cos \alpha}{c\rho g} \quad (2.4.3)$$

where,

$h_c$  is the height of rise (m)

T is surface tension of water

$\cos \alpha$  is the contact angle of water and capillary wall,

c is radius of the capillary (m)

$\rho$  is density of liquid ( $\text{kg/m}^3$ )

g is force of gravity, a constant of  $9.81 \text{ m/sec}^2$

For water calculations, the surface tension, the contact angle (1), the density ( $1000 \text{ kg/m}^3$ ) and the force of gravity can be combined and simplified to:

$$h_c = \frac{0.153}{c} \quad (2.4.4)$$

**Table 7:** Typical Height of Capillary Fringe

S.No.	Material	Grain Size (mm) <sup>a</sup>	Pore Radius (cm) <sup>b</sup>	Capillary rise (cm)	
1	Coarse Gravel	-	0.4	-	0.38 <sup>b</sup>
2	Fine Gravel	5-2	-	2.5 <sup>a</sup>	-
3	Very Coarse Sand	2-1	-	6.5 <sup>a</sup>	-
4	Coarse Sand	1-0.5	0.05	13.5 <sup>a</sup>	3.0 <sup>b</sup>
5	Medium Sand	0.5-0.2	-	24.6 <sup>a</sup>	-
6	Fine Sand	0.2-0.1	0.02	42.8 <sup>a</sup>	7.7 <sup>b</sup>
7	Silt	0.1-0.05	0.001	105.5 <sup>a</sup>	150 <sup>b</sup>
8	Silt	0.05-0.02	-	200 <sup>a</sup>	-
9	Clay	-	0.005	-	300 <sup>b</sup>

Source: a-(Reid et al., 1987), b-(Fetter, 1980)

## 2.5 Design, operation and control of groundwater recharge systems

U.S. Department of Interior (1990) described the USBR (U.S Bureau of Reclamation) solution to calculate the rate of discharge for open boreholes as follows

$$Q_i = \frac{2\pi KH^2}{\ln \left[ \frac{H}{r} + \sqrt{1 + \left( \frac{H}{r} \right)^2} \right] - \frac{\sqrt{1 + (H/r)^2}}{H/r} + \frac{1}{H/r}} \quad (2.5.1)$$

where,

$Q_i$  is discharge rate ( $L^3/T$ )

$K$  is saturated hydraulic conductivity ( $L/T$ )

$H$  is depth of the recharge gallery ( $L$ )

$r$  is radius of recharge gallery ( $L$ )

Hantush (1967) presented the following equations for predicting the maximum height of the water table beneath a circular and rectangular recharge area. Equation 2.5.2 describes the mound height.

$$h_m^2 - h_i^2 = \frac{wvt}{2K} \left\{ S^* \left( \frac{l+x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}} \right) + S^* \left( \frac{l+x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}} \right) \right. \\ \left. + S^* \left( \frac{l-x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}} \right) + S^* \left( \frac{l-x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}} \right) \right\} \quad (2.5.2)$$

$$S^*(\alpha, \beta) = \int_0^1 \operatorname{erf} \left( \frac{\alpha}{\sqrt{\tau}} \right), \operatorname{erf} \left( \frac{\beta}{\sqrt{\tau}} \right) d\tau \quad (2.5.3)$$

$$v = \frac{K\bar{b}}{\epsilon} \quad (2.5.4)$$

$$\bar{b} = 0.5[h_i(0) + h(t)] \quad (2.5.5)$$

where,

$h_m$  is maximum height of mound above aquifer base

$h_i$  is initial height of water table above aquifer base

$\epsilon$  is storativity (specific yield)

$\bar{b}$  is constant of linearization

$v$  is diffusivity

$t$  is time of recharge

$l$  is half length of recharge structure

$a$  is half width of recharge structure

$x$  is the distance from recharge structure in  $x$  direction

$y$  is the distance from recharge structure in  $y$  direction

$\operatorname{erf}$  is error function

$\tau$  is dummy variable of integral function

$S^*$  is an integral expression

Massmann et al., (2003) reports the results of computer simulations that were based on the geometry and observed geology beneath the Lacey-Lid infiltration pond in Thurston County, Washington as described in the Water Resources Investigations Report (Drost et al., 1998). Based on the results of these computer simulations, the

effective gradient under steady-state conditions beneath a medium-sized infiltration facility can be approximated with the following expression:

$$Gradient = i \approx \frac{D_{wt} + D_{gallery}}{138.62(K^{0.1})} CF_{size} \quad (2.5.6)$$

where,

$D_{wt}$  is the depth in feet from the base of the infiltration facility to the water table or to the first low-permeability layer

$D_{gallery}$  is the depth in feet of water in the gallery or infiltration facility

$CF_{size}$  is the correction factor for gallery size

The correction for the infiltration facility's size,  $CF_{size}$ , is given by the following expression:

$$CF_{size} = 0.73(A_{gallery})^{-0.76} \quad (2.5.7)$$

where,

$A_{gallery}$  is area of infiltration facility bottom in acres

Computer simulations described in Massmann et al., (2003) also suggest that infiltration facilities with large aspect ratios have higher infiltration rates than those with lower aspect ratios. Correction factor to account for these results can be described by following equation

$$CF_{aspect} = 0.02A_{ratio} + 0.98 \quad (2.5.8)$$

where,

$CF_{aspect}$  is correction factor for aspect ratio

$A_{ratio}$  is the aspect ratio for the facility (length/width)

In no case, the correction factor for aspect ratio should be greater than 1.4.

Massmann et al., (2003) suggests that reductions in hydraulic conductivity due to bottom clogging from siltation and bio-fouling may have effects on overall infiltration rates and gradients. The correction factors for siltation and biofouling and for aspect ratio are multiplied by the infiltration rate and given as follows

$$f_{corr} = (CF_{silt/bio})(CF_{aspect})f = (CF_{silt/bio})(CF_{aspect})Ki \quad (2.5.9)$$

where,

$CF_{silt/bio}$  is the correction factor for siltation and biofouling

$f$  is the “uncorrected” infiltration rate

**Table 8:**  $CF_{silt/bio}$  ratio for different facilities

S.No.	Type of Facility	$CF_{silt/bio}$
1	Not Maintained	0.3
2	Only Silt Fouling	0.5
3	Partially Maintained	0.9
4	Maintained	1

Source: (Massmann J. W., 2003)

Combining equation 2.5.6, 2.5.7 and 2.5.9 the equation can be written as

$$Q_{gallery} = KiA_{total} \quad (2.5.10)$$

$$\approx K \left[ \frac{D_{wt} + D_{gallery}}{138.62(K^{0.1})} CF_{size} \right] (CF_{silt/bio})(CF_{aspect})A_{total}$$

where,

$A_{total}$  is the total area of infiltration surface (both side and bottom)

$A_{total}$  can be given by following equation

$$A_{total} = A_{bottom} + A_{sides} \quad (2.5.11)$$

where,

$A_{sides}$  is the cross-sectional area of the submerged gallery sides in a vertical plane

$A_{\text{bottom}}$  is the cross-sectional area of the gallery bottom in a horizontal plane

Siriwardene et al., (2007) has described a method to estimate the percent reduction in the output rate of infiltration based on the cumulative mass of sediments received at the surface of the soil.

$$Q_{out\%} = \frac{100\alpha}{(\alpha + Mass^{\beta}_{<6})} \quad (2.5.12)$$

where,

$Q_{out\%}$  is the outflow rate (% of initial outflow rate)

$\alpha, \beta$  are regression coefficients,  $\alpha=1.68E^{13}$  and  $\beta=6.03$  (for fluctuating flows)

$Mass^{\beta}_{<6}$  is cumulative mass of sediments less than 6  $\mu\text{m}$  in size in  $\text{g}/\text{m}^2$

Objective of the work is to design recharge facilities that can artificially recharge groundwater by stormwater. For the purpose of the study, two sub-watersheds are selected, one in urban and the other in rural setting.

The present work was divided into different work elements to achieve the objectives of artificial recharge of groundwater by stormwater. The work elements are:

1. Review of the groundwater recharge systems and their design, operation and control
2. Development of protocol for the design of groundwater recharge facility Study
3. Collection of background information
4. Design of recharge facility

### **3.1 Review of the groundwater recharge systems and their design, operation and control**

An extensive and in-depth literature survey from various papers published in journals, books, case studies and reports, was done to cover the following aspects.

- to understand the various recharge systems being used
- to decide on the type of recharge systems that can be used for the case studies taken up in this work
- to develop a design protocol for the selected recharge systems
- to operate and control the recharge systems

### **3.2 Development of protocol for the design of groundwater recharge facility**

The existing design protocols cannot be adopted, as these require testing of a number of parameters on site of recharge whereas, the need of the hour is a design protocol which can be easily used with minimum information, that can be acquired from local drillers, municipal corporation or water supply department. Hence based on review of literature, step-by-step procedure followed for the design of the recharge facilities were standardized and presented as a protocol to aide in the design of the recharge facilities.

Urban areas in India are densely populated which makes the availability of land a major constraint in the design of any reclamation or waste management structure. Low availability of land increases the cost of the structure built hence increasing the capital cost in development and payback period of these facilities. Infiltration facilities designed in such an area should be planned taking the following aspects in mind

- should require less land cover
- should be underground, if possible
- should require less manpower to operate and maintain
- if underground, should require less opening of facility for monitoring and/or maintenance
- the designed period should be long enough
- should be able to infiltrate all the stormwater collected in a short duration of time

Whereas, rural areas are not so populated as urban areas and have plenty of land available and can have elaborate design. There is no constraint in terms of manpower required to operate and maintain the facility.

The requisites in design of urban facilities make them costly to install and operate while the facilities in rural areas are much cheaper to install and operate. Based on the above conditions, in the present study two facilities were selected, one for urban and other for rural area. The facilities selected are as follows:

1. Underground infiltration well (for urban area)
2. Infiltration gallery (for rural area)

### **3.3 Collection of background information**

Collection of background information involved hydrological, hydrogeological and site surface studies of the selected sub-watersheds. The information required for the design purpose are:

1. 90-percentile storm hydrograph
2. Characteristics of the stormwater to be discharged
3. Soil profile (strata chart)

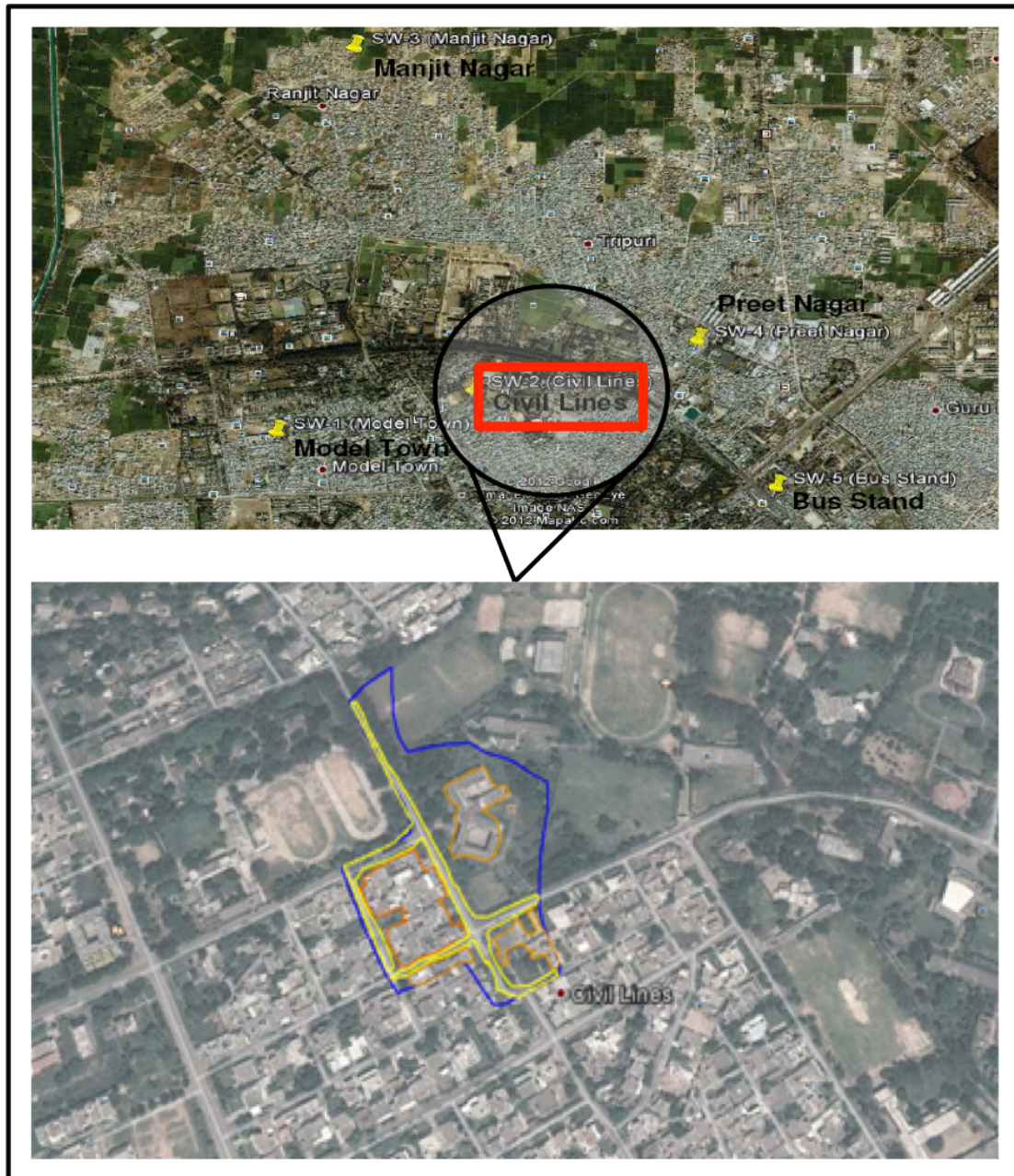
4. Depth to the aquifer
5. Initial Saturated thickness of the aquifer
6. Saturated hydraulic conductivity
7. Type of aquifer
8. Storativity

The selected sub-watersheds are:

1. Civil lines, Patiala (Punjab), India
2. Chhapa village, distt. Barnala (Punjab), India

### **3.3.1 Civil lines, Patiala (Punjab), India**

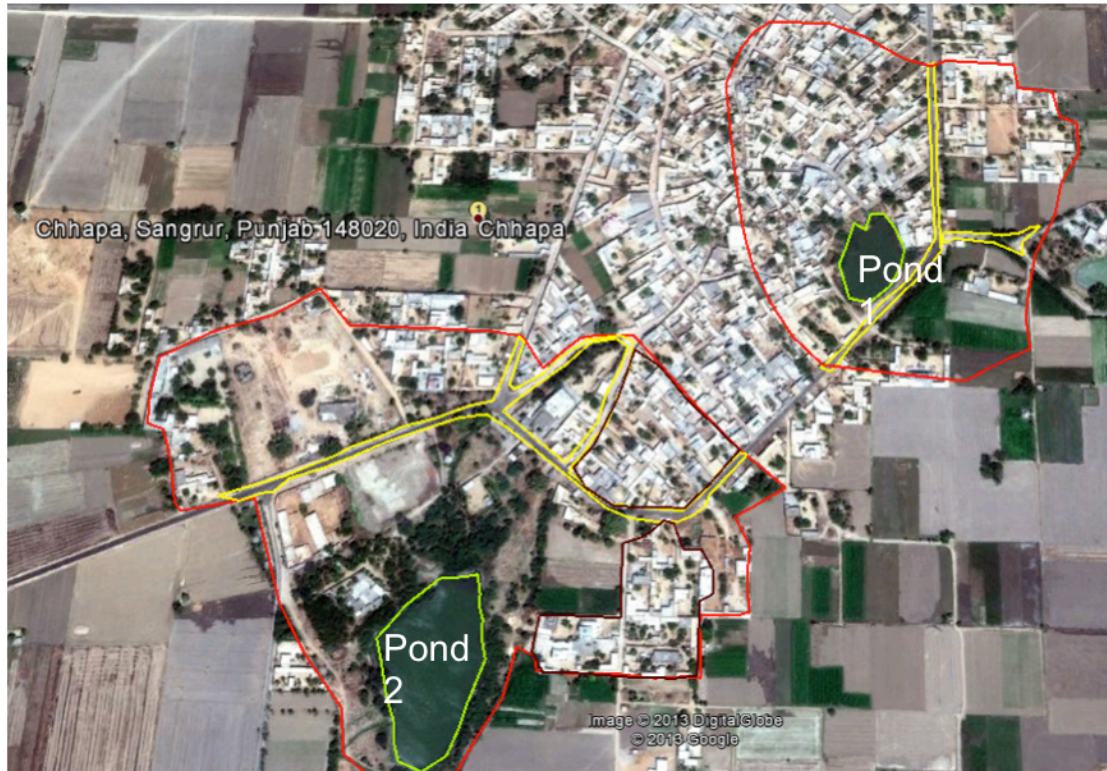
Patiala, princely city of state of Punjab, doesn't have provisions for the stormwater drainage as a result even modest rainfall events produce severe flooding in many parts of the city. This catchment within the city Patiala is a Residential area having high intensity of urbanization. It is marked by the presence of houses, school and parks. This area faces problems of open defecation, open urination, MSW dumping and stormwater. The stormwater in this area collects in an arbitrary outlet, which is formed by sloping the roads toward it. Few underground sewers or tanks are created for passage of stormwater but are not well managed and often remain blocked. The following map (Figure 1) shows the location of the selected sub-watershed within Patiala and Figure 2 shows the detailed map of the sub-watershed. The following figure shows the location of sub-watershed of Civil lines in Patiala and the detailed view demarcating the boundary of the sub-watershed.



**Figure 1:** Location of sub-watershed of Civil lines in Patiala

### **3.3.2 Chhapa village, distt. Barnala (Punjab), India**

The rural areas within Punjab severely lack facilities for stormwater drainage. The concept of stormwater management has not even reached out to most of the villages in Punjab. Chhapa has two ponds located with the village where the runoff from rainfall event ultimately reaches out. These ponds receive open urination, open defecation, MSW dumping, municipal sewage flooding, open-discharge of sewage and stormwater runoff. Our area of interest is the sub-watershed of the second pond.



**Figure 2:** Detailed view of sub-watershed of Chhapa village

### **3.4 Design of recharge facility**

The design protocol was followed to design the recharge facilities at Civil lines, Patiala and Chhapa village, distt. Barnala using the background information collected at respective sites.

At Civil lines, Patiala the design protocol for the infiltration well was followed to dispose the stormwater collected from the sub-watershed.

At Chhapa village, distt. Barnala the design protocol for the infiltration gallery was followed to dispose the stormwater collected at the second pond of the sub-watershed.

## Chapter 4

### ARTIFICIAL RECHARGE: AN OVERVIEW

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#### 4.1 Artificial recharge

Artificial recharge of groundwater is accomplished by applying water to the soil for infiltration and downward movement through the unsaturated or “vadoze” zone to the ground- water. Where permeable surface soils are not available but sufficiently permeable material is found at relatively small depth, artificial recharge can be achieved with excavated basins that are sufficiently deep to reach the permeable material. If the permeable material is too deep for removal of overlying material, but is within trenchable depth seepage trenches can be used. Such trenches are also suitable where soils are highly stratified with alternating layers of fine and coarse materials. Where permeable material is too deep for trenches, large-diameter wells, pits, or shafts in the vadose zone can be used. Both trenches and shafts are backfilled with coarse sand or fine gravel to prevent caving. Where permeable surface soils are not available, vadose zones are not sufficiently permeable to transmit water to the underlying aquifer, or aquifers are confined, artificial recharge can be achieved by applying water to recharge wells penetrating the aquifer. The type of recharge structure to be used also depends on the land availability for the installation of the structure. Trenches and shafts may be preferable in urban areas where the land availability is low and cost is high whereas, in rural areas no such restrictions exist hence large diameter pits, wells or excavated basins may be used (Bouwer, Artificial recharge of groundwater: hydrogeology and engineering, 2002).

Ground water recharge system depends upon:

- Local conditions of soil
- Hydrogeology
- Topography
- Water quality and availability (continuous/interrupted supply)
- Climate

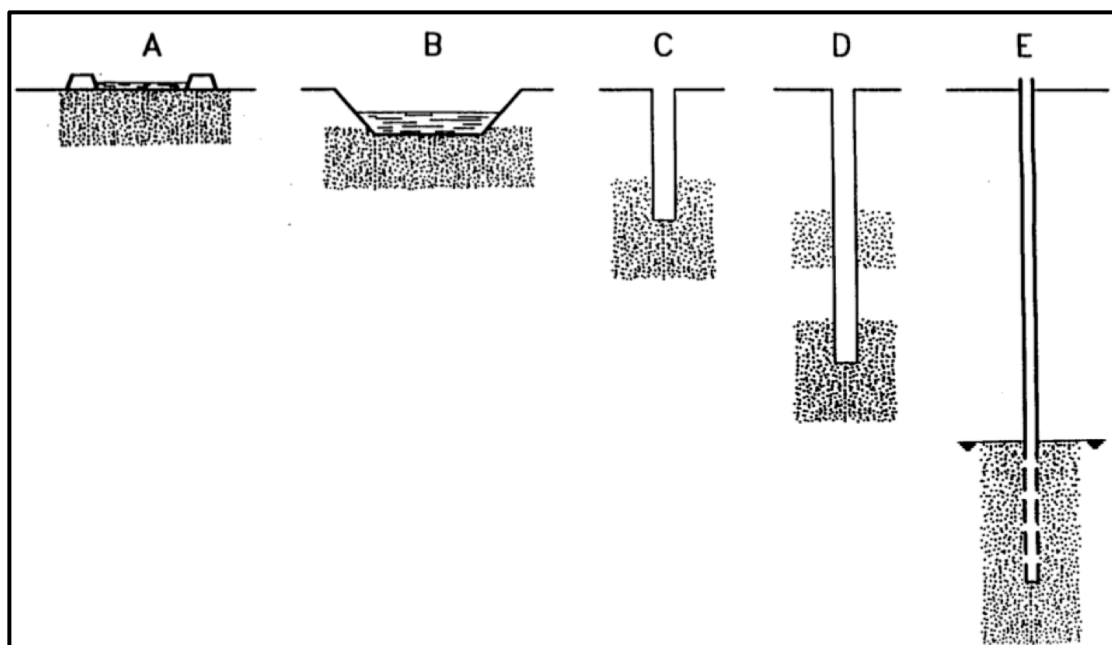
The selection groundwater recharge system is based upon:

- soil and hydrogeological information

- pretreatment of water required to minimize clogging of infiltrating soil
- clogging layers are easier to control (or remove) in surface systems
- proper pretreatment is important for trenches, shafts and wells

#### 4.2 Recharge Systems

The first step in planning and designing an artificial recharge system is selecting the type of system to be used, based on soil and hydrogeological information. Often, the choice is obvious or determined by other factors such as high cost of land in urban areas, which preclude the use of surface systems or excavated basins. Another important factor in the selection of the type of recharge system is the pretreatment of the water required before recharge to minimize clogging of the infiltrating soil surface in basins or of the walls in trenches, shafts, and wells. Since clogging layers are easier to control and remove in surface systems, proper pretreatment is especially important for trenches, shafts, and wells. Since trenches and shafts are relatively inexpensive, they can be replaced when their useful life has come to an end. On the other hand, recharge wells, while much more expensive than trenches and shafts, are more amenable to clogging (Bouwer, *Artificial recharge of groundwater: hydrogeology and engineering*, 2002).



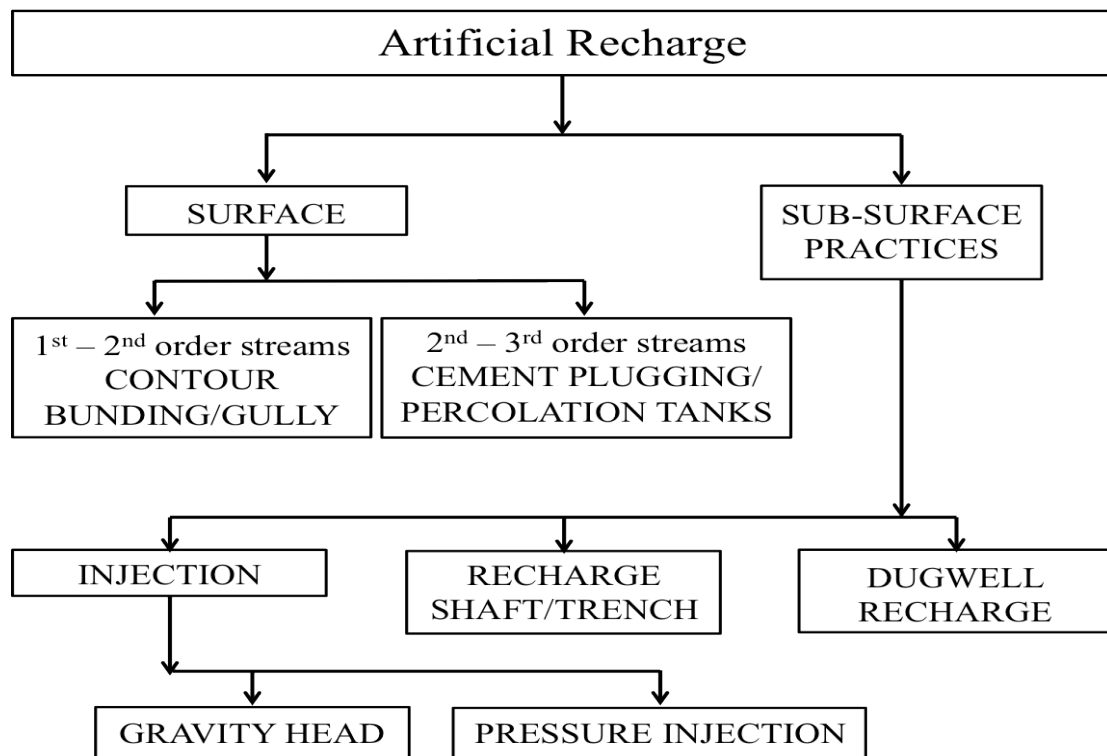
Source: (Bouwer, *Artificial recharge of groundwater: hydrogeology and engineering*, 2002)

**Figure 3:** Recharge systems: surface basin (A), excavated basin (B), trench (C), shaft or vadoze zone well (D) and aquifer well (E)

### 4.3 Methods of recharge

A variety of systems have been developed to recharge groundwater. They can be characterized into two broad categories (Central Ground Water Board, 2011) (i) Direct and (ii) Indirect:

- a) Direct surface techniques
  - i. Flooding
  - ii. Basins or percolation tanks
  - iii. Stream augmentation
  - iv. Ditch and furrow system
  - v. Recharge basins
  - vi. Over irrigation
  
- b) Direct sub surface techniques
  - i. Injection or recharge wells
  - ii. Recharge pits and shafts
  - iii. Dug well recharge
  - iv. Bore hole flooding
  - v. Natural openings, cavity fillings
  
- c) Combination surface – sub-surface techniques
  - i. Basin or percolation tank with pit shafts or wells
  
- d) Indirect techniques
  - i. Induced recharge from surface water source
  - ii. Aquifer modification
  - iii. Groundwater conservation structures



Source: (Central Ground Water Board, 2011)

**Figure 4:** Flowchart showing various recharge methods

#### 4.4 Clogging

The biggest setback in an artificial recharge system is clogging of infiltrating surface. Clogging is caused by inorganic (clay, silt) and organic (algae, sludge) suspended solids in the water that accumulate on the infiltrating surface, and by microorganisms that grow on the soil particles (biofilms) and produce polysaccharides and other insoluble metabolites to form a soil-clogging biomass. Bacteria also can produce gases (nitrogen, methane, carbon dioxide) that can block soil pores. Gas also can be formed in aquifers when water from recharge wells contains entrained air or is cooler than the groundwater itself. As the recharge water then warms up in the aquifer, dissolved air may go out of solution to form pore blocking air pockets in the aquifer (called air binding). Since clogging layers are much less permeable than the natural soil material, they reduce infiltration rates and become the controlling factor or “bottleneck” in the infiltration process (Bouwer, Artificial recharge of groundwater: hydrogeology and engineering, 2002).

Clogging is best controlled by prevention; that is, by removing the parameters that

cause clogging. For surface infiltration systems, clogging is controlled by periodically drying the basins or other infiltration facility, and letting the clogging layer dry, decompose, shrink, crack, and curl up. This may be sufficient to restore infiltration rates to satisfactory values. If clogging materials continue to accumulate, they must be periodically removed at the end of a drying period. This can be done mechanically with scrapers, front-end loaders, graders, or manually with rakes. After removal of the clogging material, the soil should be disked or harrowed to break up any crusting that may have developed at or near the surface. Disking or plowing clogging layers as such into the soil gives short-term relief, but eventually fines and other clogging materials will accumulate in the topsoil and the entire disk or plow layer must be removed (Bouwer, Artificial recharge of groundwater: hydrogeology and engineering, 2002). For sub-surface infiltration systems, pretreatment of stormwater becomes a necessary requisite before recharging it to groundwater, to avoid clogging, as sub-surface infiltration systems are costly to build and maintain.

#### **4.5 Pretreatment**

Any material present in stormwater, which may cause problems in its infiltration to groundwater through artificial recharge, needs to be removed. This may be organic or inorganic in nature or may be microorganisms. Materials such as suspended solids, organic impurities and microorganisms can clog the pore space of soil in turn reducing the infiltration rate.

Methods of pretreatment (Draft Green Infrastructure Supplemental Stormwater Document, 2009):

- a) Filter
- b) Bioretention
- c) Filter Strips
- d) Appropriate prefabricated and proprietary design
- e) Sumped inlets with traps
- f) Combination of two or more technologies

## **4.6 Studies required for design of recharge system**

### **4.6.1 Hydro-meteorological studies**

These studies are undertaken to understand the rainfall pattern and evaporation losses and thereby to determine the amount of water that would be available from a given catchment and the size of storages to be built. The main factors to be considered are:

- Minimum annual rainfall during the previous 10 years
- Number of rainy spells in a rainy season and duration of each spell
- Amount of rainfall in each rainy spell
- Rainfall intensity (maximum) 3 hourly, 6 hourly etc. as may be relevant for a region. As a general guide, the one, which causes significant runoff and local flooding, should be adopted.

### **4.6.2 Hydrogeological studies**

A detailed hydrogeological study of the project area and also the regional picture of hydrogeological setting is necessary to know precisely the promising locations for recharge and the type of structures to be built for the purpose. The aspects to be considered for a recharge scheme are:

#### **Detailed information and maps showing**

- Hydrogeological units demarcated on the basis of their water bearing capabilities at both shallow and deeper levels
- Ground water contours to determine the form of the water table and hydraulic connection of ground water with rivers, canals etc.
- Depth to water table (maximum, minimum and mean)
- Amplitude of water level fluctuations
- Piezometric head in deeper aquifers and their variation with time
- Ground water potential of different hydrogeological units and the level of ground water development
- Chemical quality of water in different aquifers

#### **Information from local open wells**

Artificial recharge schemes are site-specific and even the replication of the proven techniques are to be based on the local hydrogeological and hydrological conditions.

However, following information from local wells needs to be taken into consideration in planning such schemes:

- The unsaturated thickness of rock formations occurring beyond 3 meters below ground level should be considered to assess the requirement of water to build up the sub-surface storage. The ground water recharge process should aim at saturating this entire unsaturated zone (also known as vadoze zone)
- The upper 3 m of the unsaturated zone should not be considered for recharging since it may cause adverse environmental impacts like water logging, soil salinity etc.
- The post-monsoon depth to water level represents a situation of minimum thickness of vadoze zone available for recharge. This should be considered vis-à-vis the available surplus runoff in the area.

#### 4.7 Darcy's law

Henri Darcy established empirically that the flux of water through a permeable formation is proportional to the distance between top and bottom of the soil column. The constant of proportionality is called the hydraulic conductivity (K)

$$Q = V.A \quad (4.7.1)$$

where,

Q is rate of discharge [ $L^3/T$ ]

V is specific discharge [ $L/T$ ]

A is the area of recharge [ $L^2/T$ ]

$$V \propto -\Delta h \quad (4.7.2)$$

where,

$\Delta h$  is head loss

$$V \propto 1/\Delta L \quad (4.7.3)$$

where,

$\Delta L$  is depth

Hence,

$$Q = -K.A(dh/dl) \quad (4.7.4)$$

#### 4.8 Saturated hydraulic conductivity

Hydraulic conductivity is a measure of the material's capacity to transmit water. Coefficient of permeability is another term used for hydraulic conductivity. It is defined as a constant of proportionality relating the specific discharge of a porous medium under a unit hydraulic gradient in the Darcy's law:

$$v = -Ki \quad (4.8.1)$$

where,

$v$  is specific discharge [L/T]

$K$  is hydraulic conductivity [L/T]

$i$  is hydraulic gradient [dimensionless]

Hydraulic conductivity is a function of water viscosity and density (in a strict sense a function of water temperature). However, given the small range of temperature variation encountered in most groundwater systems, the temperature dependence of hydraulic conductivity is often neglected.

Hydraulic conductivity can be obtained from transmissivity of an aquifer. Transmissivity of an aquifer is related to hydraulic conductivity as follows:

$$T = Kb \quad (4.8.2)$$

where,

$T$  is transmissivity [L<sup>2</sup>/T]

$b$  is aquifer thickness [L]

#### 4.9 Transmissivity

Transmissivity is a measure of how much water can be transmitted horizontally through a unit width of a fully saturated aquifer under a hydraulic gradient of 1.0.

It is the product of the hydraulic conductivity and the saturated thickness of the aquifer.

#### 4.10 Storativity

Storativity is defined as the volume of water released from storage per unit surface area of an aquifer (or aquitard) per unit decline in hydraulic head. Storativity is also known by the terms coefficient of storage and storage coefficient. When the aquifer is confined it is known as storativity while for an unconfined aquifer it is called specific yield.

#### 4.11 Porosity

Porosity is defined as the void space of a rock or unconsolidated material:

$$n = V_v/V_T \quad (4.11.1)$$

where,

$n$  is porosity [dimensionless]

$V_v$  is void volume [ $L^3$ ]

$V_T$  is total volume [ $L^3$ ].

#### 4.12 Groundwater mounds

Infiltration of storm water through soils is a transient flow process. When an infiltration basin is loaded with storm water, the soil medium between the basin and the groundwater table will undergo a storage process in which the soil water moisture varies from an unsaturated to a saturated condition. When the infiltrating water reaches the groundwater table, a water mound will begin to build up. The shape and growth of a mound depend on the infiltration rate, size of the basin, and hydraulic properties of soil medium (Ferguson, 1990).

#### **4.13 Capillary fringe**

Fluid is drawn above the saturated horizon by capillary forces. This zone is called the capillary fringe, and the fluid is in a state of tension (suction, negative pressure) (Dendrou, 1999). Capillary fringe may rise as high as 30 cm in medium sands (Bouwer, 2002), above the groundwater mound increasing the effective height of the mound.

### 5.1 Development of protocol for the design of groundwater recharge facility

Protocols for the design of underground infiltration well and infiltration gallery are described in the sections below.

#### 5.1.1 Protocol for the design of underground infiltration well

1. Following data was gathered
  - a) 90 percentile storm hydrograph for the sub-watershed/watershed
  - b) Soil profile information (strata chart) from local drillers or water supply department
  - c) Saturated hydraulic conductivity of the strata, in which the stormwater was released (most permeable layer nearest to the soil surface), from the literature
  - d) Initial saturated thickness of the aquifer, if water is not present in the aquifer the distance between the top of the impervious layer below the aquifer to the top of the aquifer layer is taken as thickness of the aquifer.
  - e) Depth to the aquifer from local drillers or water supply department
  - f) Type of aquifer from water supply department
  - g) Storativity from the above gathered information
  - h) Capillary rise from soil profile information
  
2. From the stormwater hydrograph, the rate of infiltration was decided based on the average flow rate of stormwater. If the stormwater is recharged at a rate equal to the average flow rate of stormwater in 90 percentile storm hydrograph, all the water gets recharged at the end of the duration of the hydrograph. Since, a short duration (1-1.5 hr) of flooding could be tolerated in the present case the average flow rate for infiltration was adjusted accordingly. The duration of flooding that can be tolerated depends on the maximum volume of stormwater that can be stored on the surface, the time in which the stormwater should infiltrate; after the rain stops and the maximum diameter of the well that can be allowed. To increase the time of infiltration the infiltration rate is reduced and vice-versa.

3. Using the above flow rate, diameter and depth of the infiltration well was assumed. The depth is assumed till the top of the strata in which the aquifer exists. The assumed diameter was used to calculate the rate of percolation as

$$w = \frac{Q_i}{\pi D^2/4} \quad (5.1.1.1)$$

where,

w is the rate of percolation in m/hr

D is the diameter of the pipe in m

$Q_i$  is the rate of recharge in  $m^3/hr$  given by equation 5.1.1.2

$$Q_i = \frac{2\pi KH^2}{\ln \left[ \frac{H}{r} + \sqrt{1 + \left( \frac{H}{r} \right)^2} \right] - \frac{\sqrt{1 + (H/r)^2}}{H/r} + \frac{1}{H/r}} \quad (5.1.1.2)$$

where,

$Q_i$  is rate of recharge in  $m^3/hr$

K is saturated hydraulic conductivity in m/hr

H is depth of the recharge gallery in m

r is radius of recharge gallery in m

The rate of percolation and rate of recharge was then put in equation 5.1.1.3 to calculate the diameter of the infiltration well

$$\frac{\pi D^2}{4} = Q_i \times w \quad (5.1.1.3)$$

Since mound height calculations require the length and width of the recharge facility, pipe area equivalent square (for circular recharge facility) of the infiltration well, was used. The width and length of pipe area equivalent square was calculated as given by equation 5.1.1.4.

$$L = W = \sqrt{\frac{\pi D^2}{4}} \quad (5.1.1.4)$$

where,

W is the width of the well in m

L is the length of the well in m

Mound height was calculated as follows.

$$h_m^2 - h_i^2 = \frac{wvt}{2K} \left\{ S^* \left( \frac{l+x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}} \right) + S^* \left( \frac{l+x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}} \right) \right. \\ \left. + S^* \left( \frac{l-x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}} \right) + S^* \left( \frac{l-x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}} \right) \right\} \quad (5.1.1.5)$$

$$S^*(\alpha, \beta) = \int_0^1 \operatorname{erf} \left( \frac{\alpha}{\sqrt{\tau}} \right), \operatorname{erf} \left( \frac{\beta}{\sqrt{\tau}} \right) d\tau \quad (5.1.1.6)$$

$$v = \frac{K\bar{b}}{\epsilon} \quad (5.1.1.7)$$

$$\bar{b} = 0.5[h_i(0) + h(t)] \quad (5.1.1.8)$$

where,

$h_m$  is maximum height of mound above aquifer base

$h_i$  is initial height of water table above aquifer base

$\epsilon$  is storativity (specific yield)

$\bar{b}$  is constant of linearization

$v$  is diffusivity

$t$  is time of recharge

$l$  is half length of recharge structure

$a$  is half width of recharge structure

$x$  is the distance from recharge structure in x direction

$y$  is the distance from recharge structure in y direction

erf is error function

$\tau$  is dummy variable of integral function

$S^*$  is an integral expression

Capillary rise for the soil type till the mound rises was calculated by equation 5.1.1.9.

$$h_c = \frac{0.153}{c} \quad (5.1.1.9)$$

where,

$h_c$  is the height of rise of capillary in m

$c$  is radius of the capillary/ pore size of soil in m

The new depth of the infiltration well was calculated by equation 5.1.1.10.

$$\begin{aligned} \text{New Depth} = \text{Depth to aquifer} - (\text{Mound height} \\ + \text{Capillary Rise}) \end{aligned} \quad (5.1.1.10)$$

This new depth obtained was compared to the assumed depth. The above steps were iterated till the new depth obtained became equal to the depth assumed. The depth such obtained was the maximum allowable depth of the infiltration well. The depth of the infiltration well cannot exceed this depth.

4. Then, the depth of the infiltration well was fixed according to the convenience and step-3 was repeated to obtain the new diameter of the infiltration well at the new depth.

5. Finally, the diameter of the infiltration well obtained was compared to the diameter of pipes available in the market and the diameter was fixed accordingly and step-3 was again repeated to find the maximum allowable depth.

6. Clogging was determined as reduction of the infiltration rate by 70% as given by equation 5.1.1.11

$$Q_{out\%} = \frac{100\alpha}{(\alpha + Mass^{\beta}_{<6})} \quad (5.1.1.11)$$

where,

$Q_{out\%}$  is the outflow rate (% of initial outflow rate)

$\alpha, \beta$  are regression coefficients,  $\alpha=1.68E^{13}$  and  $\beta=6.03$  (for fluctuating flows)

$Mass^{\beta}_{<6}$  is cumulative mass of sediments less than  $6 \mu\text{m}$  in size in  $\text{g/m}^2$

The clogging time was calculated as the time in which  $Q_{out\%}$  became less than or equal to 30% given by equation 5.1.1.12.

$$T_{clog} = \frac{315.67 \times A}{Q_i \times C} \quad (5.1.1.12)$$

where,

$T_{clog}$  is the clogging time (hr)

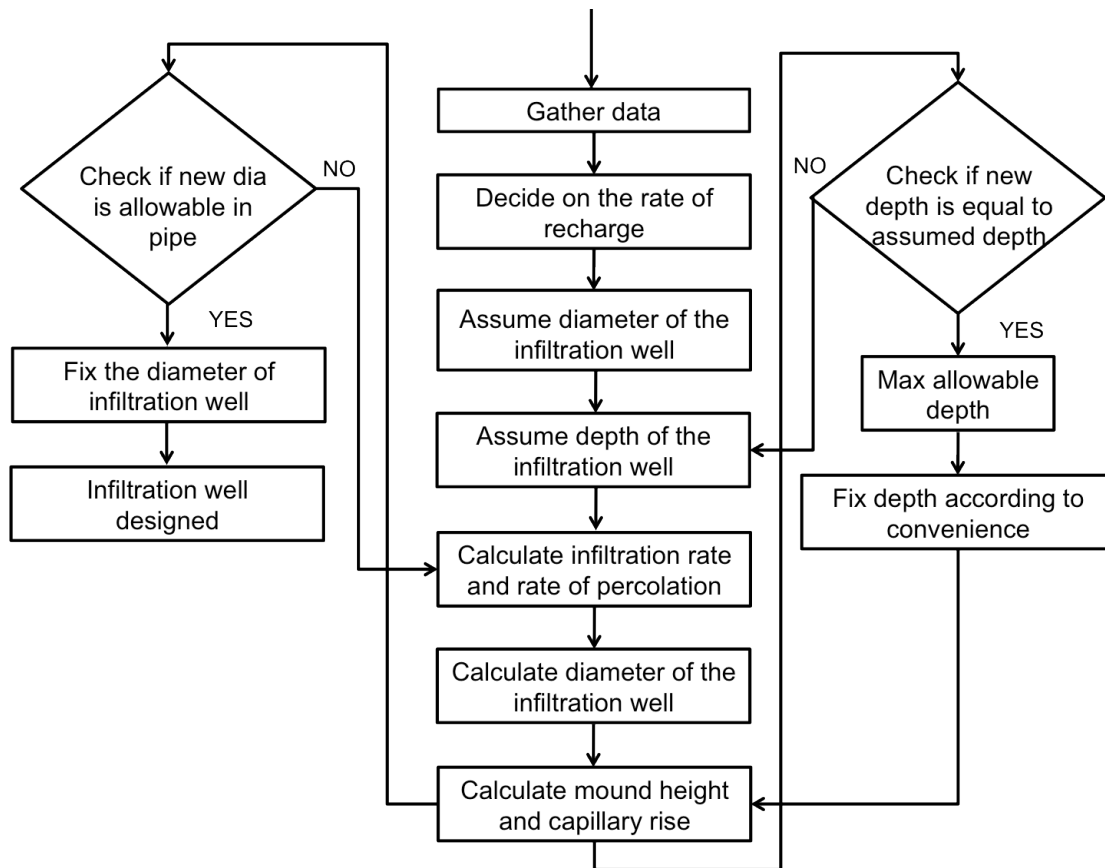
$Q$  is the rate of recharge ( $\text{m}^3/\text{hr}$ )

$C$  is the concentration of sediments less than  $6 \mu\text{m}$  in size ( $\text{g/m}^3$ )

Special filters (like bag filters) can be used to allow only turbid water to be sent into the infiltration well. The particle size of turbid particles is less than  $1 \mu\text{m}$  in size hence; the concentration of particles less than  $6 \mu\text{m}$  in size becomes negligible, thereby increasing the clogging time.

Removable candle filters can also be installed inside the infiltration well along its length, which can provide an attachment media for the growth of biofilm that can anaerobically digest the soluble BOD, and biodegradable suspended solids but can increase the biological floc formation. The clogging by this phenomenon can be calculated accordingly. These candle filters can be removed for maintenance or replacement.

The clogging material is pumped when the infiltration rate reduces.



**Figure 5:** Flowchart for design of infiltration well

### 5.1.2 Protocol for the design of infiltration gallery

1. Following data was gathered
  - a) Depth of the water that should be allowed to remain in the pond for irrigation and other purposes
  - b) 90 percentile storm hydrograph for the sub-watershed/watershed
  - c) Soil profile information (strata chart) from local drillers or water supply department
  - d) Saturated hydraulic conductivity of the strata, in which the stormwater was released (most permeable layer nearest to the soil surface), from the literature
  - e) Initial saturated thickness of the aquifer, if water is not present in the aquifer the distance between the top of the impervious layer below the aquifer to the top of the aquifer layer is taken as thickness of the aquifer.
  - f) Depth to the aquifer from local drillers or water supply department
  - g) Type of aquifer from water supply department
  - h) Storativity from the above gathered information

i) Capillary rise from soil profile information

2. From the stormwater hydrograph, the infiltration rate was decided on the basis of calculation of average flow rate of stormwater. The time of recharge is not as important in case of infiltration facilities for rural areas as the volume of the water that is being handled. The average infiltration rate was used to determine the rise in the volume of the water in the pond. The infiltration rate was adjusted as such that the excess volume of the pond (more than the fixed volume at determined depth) should infiltrate through the infiltration gallery in 6 hours after the rain stops as 6 hours is taken as the minimum gap between two events of rainfall. In any case the water level should not increase beyond the freeboard of the pond. The excess water is drained out through a drainpipe.

3. Infiltration gallery dimension was assumed on the basis of volume of excess stormwater to be infiltrated. The depth was assumed till the top of the most permeable layer near the soil surface. Circular geometry was assumed because when the infiltration gallery is empty it can cave in due to the pressure of the water outside the gallery. The gallery should not be very deep as it can compress the clogging layer hence reduce the permeability.

4. The hydraulic gradient was calculated by the following equation.

$$Gradient = i \approx \frac{D_{wt} + D_{gallery}}{138.62(K^{0.1})} CF_{size} \quad (5.1.2.1)$$

where,

$D_{wt}$  is the depth in feet from the base of the infiltration facility to the water table or to the first low-permeability layer

$D_{gallery}$  is the depth in feet of water in the gallery or infiltration facility

$CF_{size}$  is the correction factor for gallery size

5. Infiltration rate was calculated by Darcy's equation after applying corrections for size, aspect ratio, silting, bio fouling and infiltration from the sides of the gallery.

$$Q_{gallery} = KiA_{total} \quad (5.1.2.2)$$

$$\approx K \left[ \frac{D_{wt} + D_{gallery}}{138.62(K^{0.1})} CF_{size} \right] (CF_{silt/bio})(CF_{aspect})A_{total}$$

where,

$CF_{size}$  is the correction factor for gallery size

$CF_{silt/bio}$  is the correction factor for siltation and biofouling

$CF_{aspect}$  is correction factor for aspect ratio

$A_{total}$  is the total area of infiltration surface (both side and bottom)

$$CF_{size} = 0.73(A_{gallery})^{-0.76} \quad (5.1.2.3)$$

where,

$A_{gallery}$  is the area of the infiltration gallery in acres

$$CF_{aspect} = 0.02A_{ratio} + 0.98 \quad (5.1.2.4)$$

where,

$A_{ratio}$  is the aspect ratio for the gallery (length/width)

$$A_{total} = A_{bottom} + A_{sides} \quad (5.1.2.5)$$

where,

$A_{sides}$  is the cross-sectional area of the submerged gallery sides in a vertical plane

$A_{bottom}$  is the cross-sectional area of the gallery bottom in a horizontal plane

6. Rate of percolation was calculated as give in equation 5.1.2.6

$$w = \frac{Q_{gallery}}{\pi D^2/4} \quad (5.1.2.6)$$

where,

D is the assumed diameter of the gallery

7. From rate of percolation and the average flow rate the diameter of the infiltration gallery was calculated from the flow rate calculated for the flow excess of the average flow rate.

8. Since mound height calculations require the length and width of the recharge facility, pipe area equivalent square (for circular recharge facility) of the infiltration well, was used. The width and length of pipe area equivalent square was calculated as given by equation 5.1.2.7.

$$L = W = \sqrt{\frac{\pi D^2}{4}} \quad (5.1.2.7)$$

where,

W is the width of the well in m

L is the length of the well in m

Mound height was calculated as follows.

$$h_m^2 - h_i^2 = \frac{wvt}{2K} \left\{ S^* \left( \frac{l+x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}} \right) + S^* \left( \frac{l+x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}} \right) + S^* \left( \frac{l-x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}} \right) + S^* \left( \frac{l-x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}} \right) \right\} \quad (5.1.2.8)$$

$$S^*(\alpha, \beta) = \int_0^1 \operatorname{erf} \left( \frac{\alpha}{\sqrt{\tau}} \right), \operatorname{erf} \left( \frac{\beta}{\sqrt{\tau}} \right) d\tau \quad (5.1.2.9)$$

$$v = \frac{K\bar{b}}{\epsilon} \quad (5.1.2.10)$$

$$\bar{b} = 0.5[h_i(0) + h(t)] \quad (5.1.2.11)$$

where,

$h_m$  is maximum height of mound above aquifer base

$h_i$  is initial height of water table above aquifer base

$\epsilon$  is storativity (specific yield)

$\bar{b}$  is constant of linearization

$v$  is diffusivity

$t$  is time of recharge

$l$  is half length of recharge structure

$a$  is half width of recharge structure

$x$  is the distance from recharge structure in x direction

$y$  is the distance from recharge structure in y direction

erf is error function

$\tau$  is dummy variable of integral function

$S^*$  is an integral expression

Capillary rise for the soil type till the mound rises was calculated by equation 5.1.2.12.

$$h_c = \frac{0.153}{c} \quad (5.1.2.12)$$

where,

$h_c$  is the height of rise of capillary in m

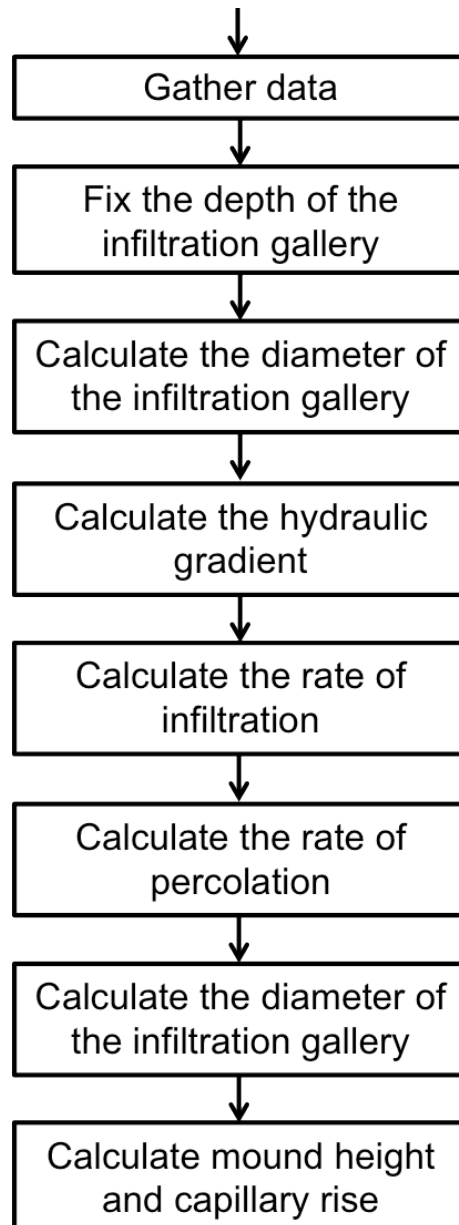
$c$  is radius of the capillary/ pore size of soil in m

9. Maximum allowable depth of the infiltration gallery was calculated as

$$\begin{aligned} & \textit{Max. Allowable Depth} \\ & = \textit{Depth to aquifer} - (\textit{Mound height} + \textit{Capillary Rise}) \end{aligned} \quad (5.1.2.13)$$

10. When the infiltration rate reduced the galley was left to dry so that the clogged material gets dried and curls up which was then scraped out and the soil layer is

disked and harrowed. Eventually the top soil layer may need to be removed and be replaced over time. However, the clogging would be minimum in the present because of the up-flow roughing filters used in series.



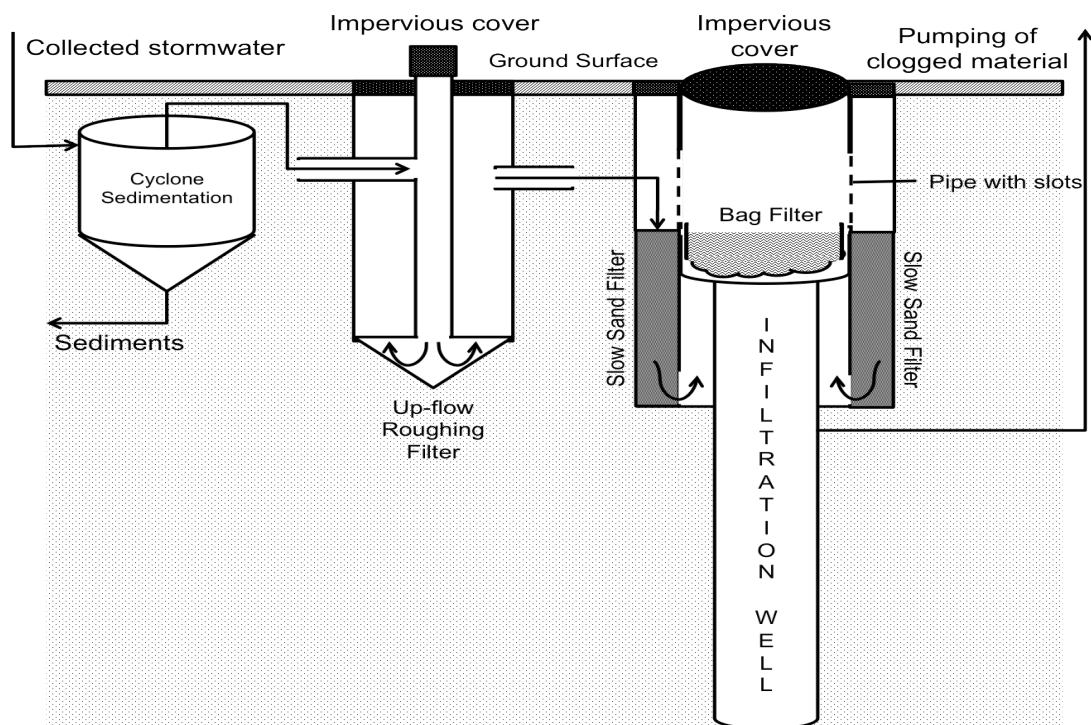
**Figure 6:** Flowchart for design of infiltration gallery

## 5.2 Design of recharge facility

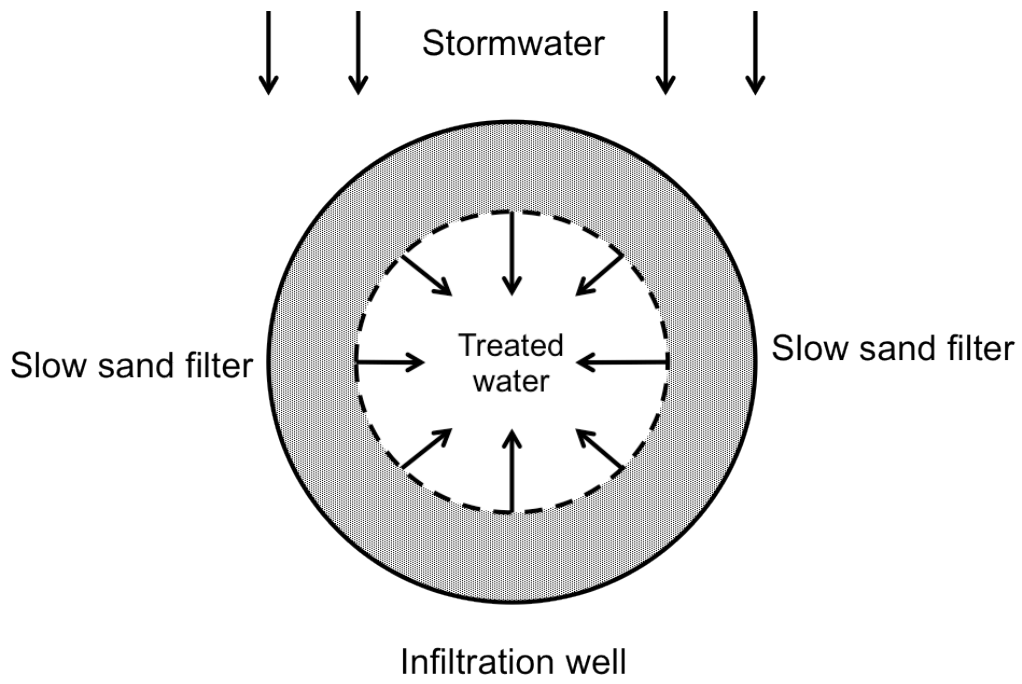
The design of recharge facilities i.e. infiltration well at Civil lines, Patiala and infiltration gallery at Chhapa village, distt. Barnala are given below.

### 5.2.1 Infiltration well at Civil lines, Patiala (Punjab)

The infiltration well at Civil lines, Patiala was designed as such that the collected stormwater was pretreated; first by cyclone sedimentation to remove suspended solids, the stormwater was then sent to the second unit, which was multigrade, multimedia up-flow roughing filter that removed, suspended solids and BOD. It was then subjected to slow sand filtration to remove other organic impurities, biomass and further reduce the concentration of suspended solids. The slow sand filter was arranged on the periphery of the infiltration well and the stormwater after filtration moved in upward direction to enter the infiltration well. This arrangement was made to prevent the slow sand filter from drying up. Hence, the slow sand filter always remained wet, even if there was no stormwater to be recharged. After pretreatment, the treated stormwater was allowed to enter the infiltration well, via which it was recharged into the groundwater. The figure given below gives a schematic description of the facility installed.



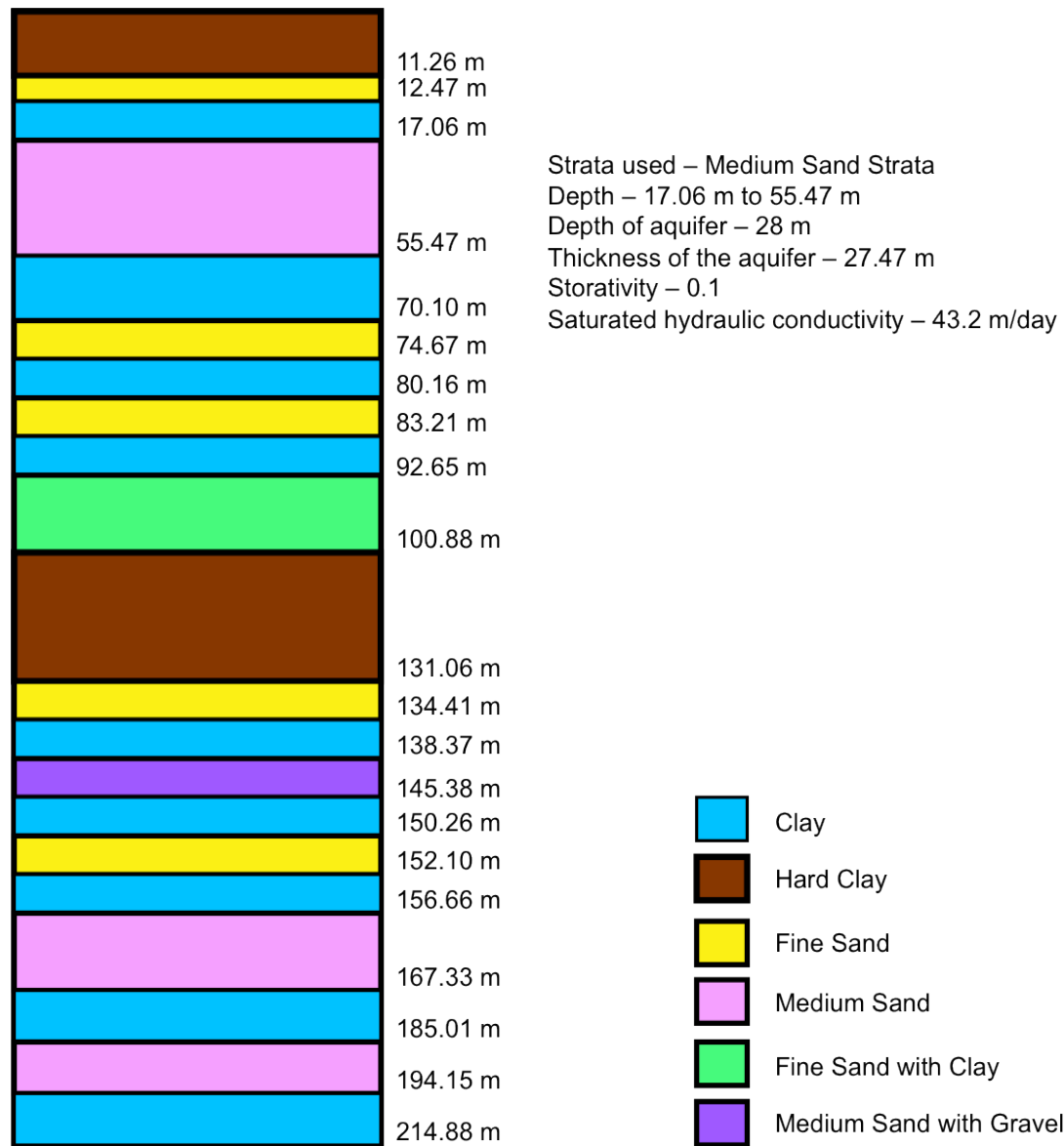
**Figure 7:** Schematic of infiltration well



**Figure 7a:** Filter assembly of infiltration well

### 5.2.1.1 Soil profile (strata chart)

The following figure (figure 8) gives the soil strata chart near Civil lines, Patiala



**Figure 8:** Soil strata chart for Civil lines, Patiala

### 5.2.1.2 Required information

The table given below lists the required information for the design of infiltration well, their values as collected or determined based on literature survey and comments on the values taken.

**Table 9:** Values of the required information for design purpose

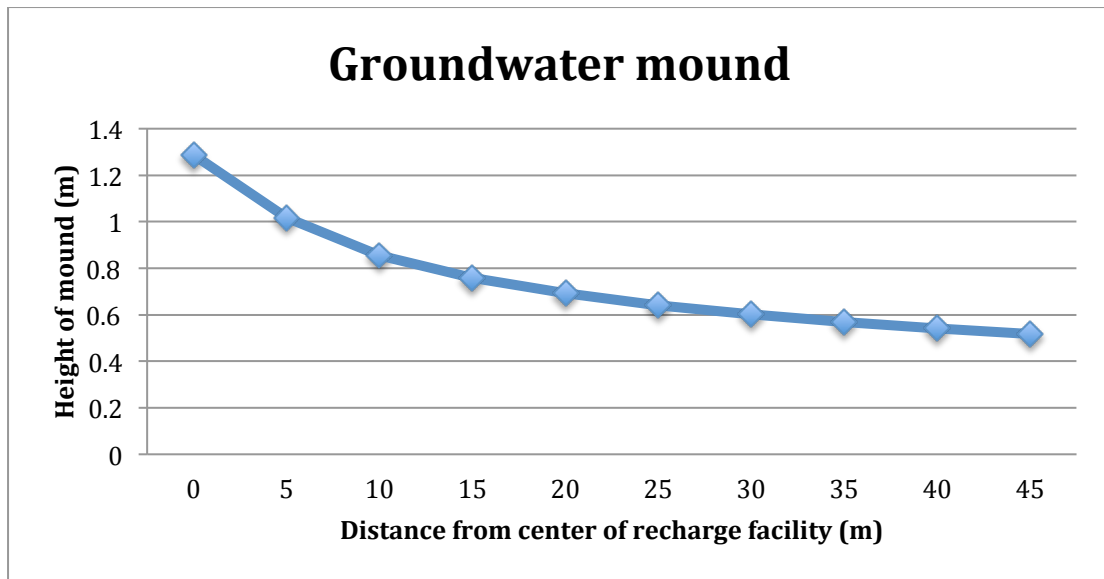
S.No.	Information	Value	Comments
1	Design infiltration rate	76.22 m <sup>3</sup> /hr	The average flow rate was 98 m <sup>3</sup> /hr. Since 1 hr of flooding is tolerated after the rain stops the infiltration rate is taken as 76.22 m <sup>3</sup> /hr
2	Depth to the aquifer	28 m	Information was obtained from the water supply department
3	Initial saturated thickness of the aquifer	27.47 m	
4	Strata used for recharge	Medium sand	Maximum hydraulic conductivity strata nearest to the soil surface
5	Saturated hydraulic conductivity	43.2 m/day	Since medium sand strata was used for recharge purpose the value was obtained from the literature
6	Type of aquifer	Unconfined	
7	Storativity	0.1	Since the aquifer is of unconfined type
8	Capillary rise	0.246 m	From literature for medium sand strata

### 5.2.1.3 Design parameters

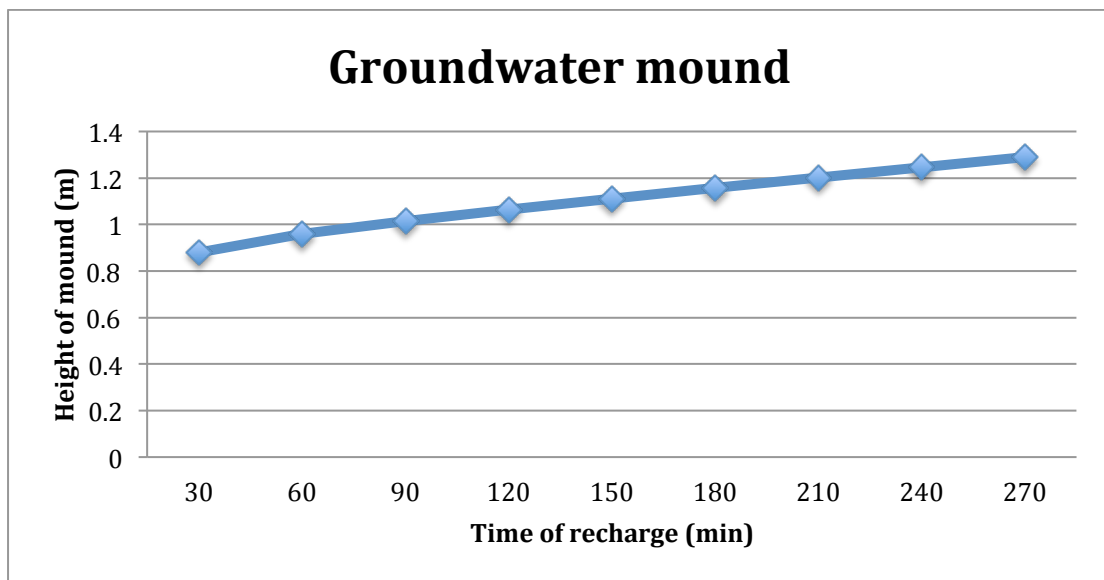
The infiltration well was designed and the design parameters are listed in the table below.

**Table 10:** Values of design parameters used in the design of infiltration well

S.No.	Design Parameter	Value
1	Diameter of the infiltration well	1.95 m
2	Maximum allowable depth	26.21 m
3	Fixed depth of the infiltration well	18 m
4	Mound height at fixed depth	1.28 m
5	Capillary rise	0.246 m
6	Rate of infiltration	75.93 m <sup>3</sup> /hr
7	Rate of percolation	25.42 m/hr



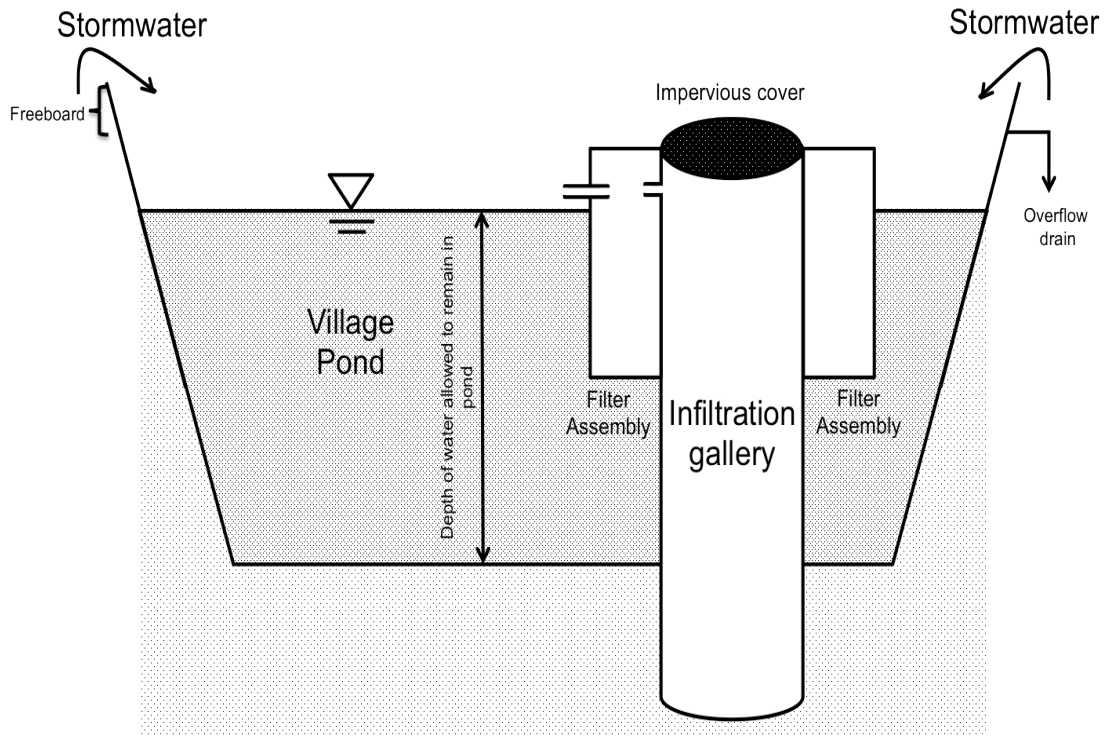
**Figure 9:** Groundwater mound height with respect to distance at infiltration well



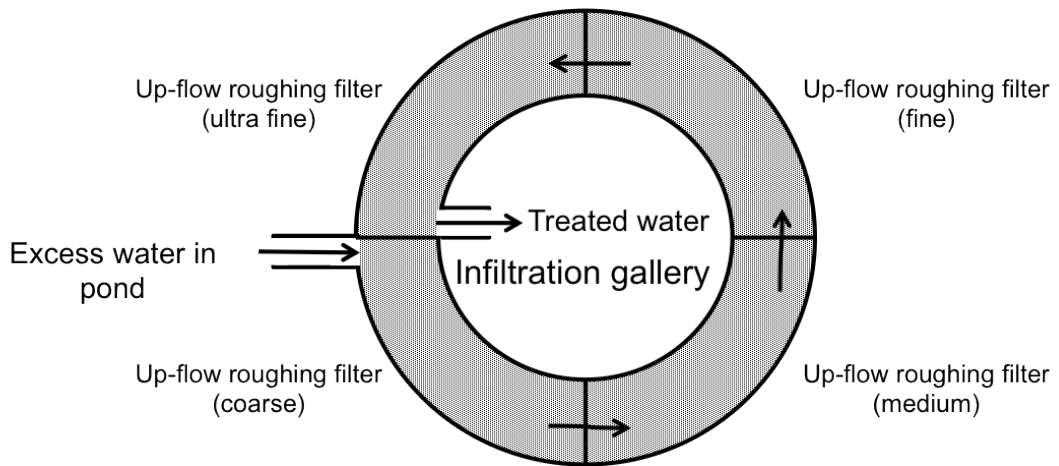
**Figure 10:** Groundwater mound height with respect to time at infiltration well

### 5.2.2 Infiltration gallery at Chhapa village, distt. Barnala (Punjab)

The infiltration gallery at Chhapa village was designed as such that all the stormwater was collected in the pond and excess water was allowed to overflow into the infiltration gallery which was first passed through slow sand filter to pretreat the stormwater for any suspended solids, organic impurities and algae cells. The stormwater after passing through the slow sand filter was made to fall into the infiltration gallery, which was then recharged into the groundwater. The figure given below gives a schematic description of the facility installed.



**Figure 11a:** Schematic of infiltration gallery



**Figure 11b:** Filter assembly of infiltration gallery

### 5.2.2.1 Soil profile (strata chart)

The following figure (figure 12) gives the soil strata chart near Civil lines, Patiala



**Figure 12:** Soil strata chart of Chhapa village (distt. Barnala)

### 5.2.2.2 Required information

The table given below lists the required information for the design of infiltration gallery, their values as collected or determined based on literature survey and comments on the values taken.

**Table 11:** Values of the required information for design purpose

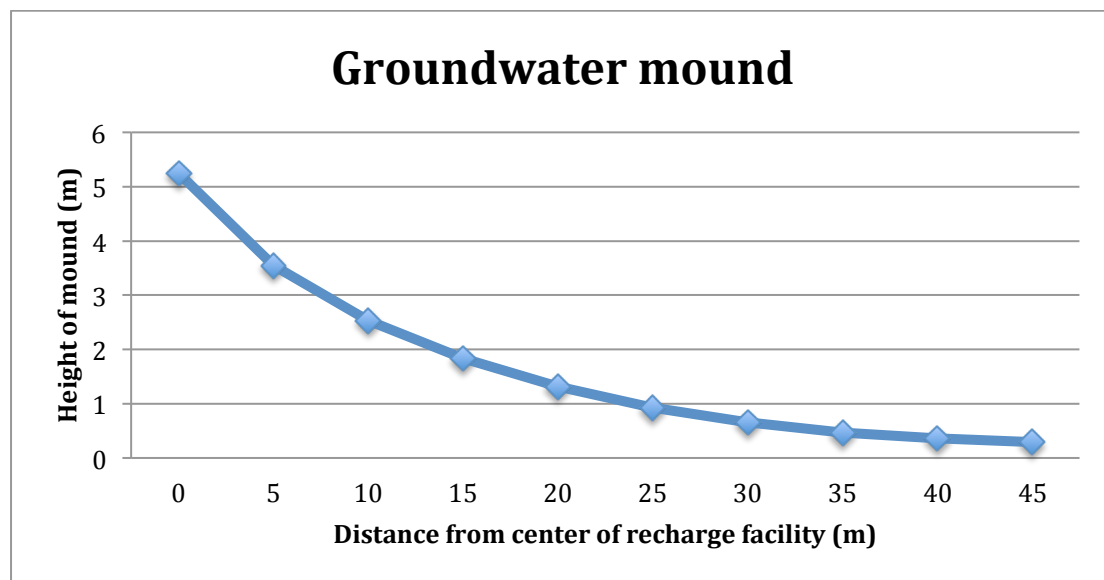
S.No.	Information	Value	Comments
1	Depth of water that should remain in the pond	1.2 m	It is based on the volume of water that should be available in pond for irrigation or other purposes. The total depth of the gallery was taken as the sum of depth of gallery below the pond and depth of the water that should be allowed to remain in the pond.
2	Maximum depth of water that can remain in pond	2.2 m	If more water enters after the pond has reached its maximum capacity, it is drained out via the drainpipe.
3	Design infiltration rate	77.01 m <sup>3</sup> /hr	Based on excess volume of stormwater entering the pond to be recharged
4	Depth to the aquifer	9 m	Information was obtained from the water supply department
5	Initial saturated thickness of the aquifer	2 m	
6	Strata used for recharge	Medium sand	Maximum hydraulic conductivity strata nearest to the soil surface
7	Saturated hydraulic conductivity	43.2 m/day	Since medium sand strata was used for recharge purpose the value was obtained from the literature
8	Type of aquifer	Unconfined	
9	Storativity	0.1	Since the aquifer is of unconfined type
10	Capillary rise	0.246 m	From literature for medium sand strata

### 5.2.2.3 Design parameters

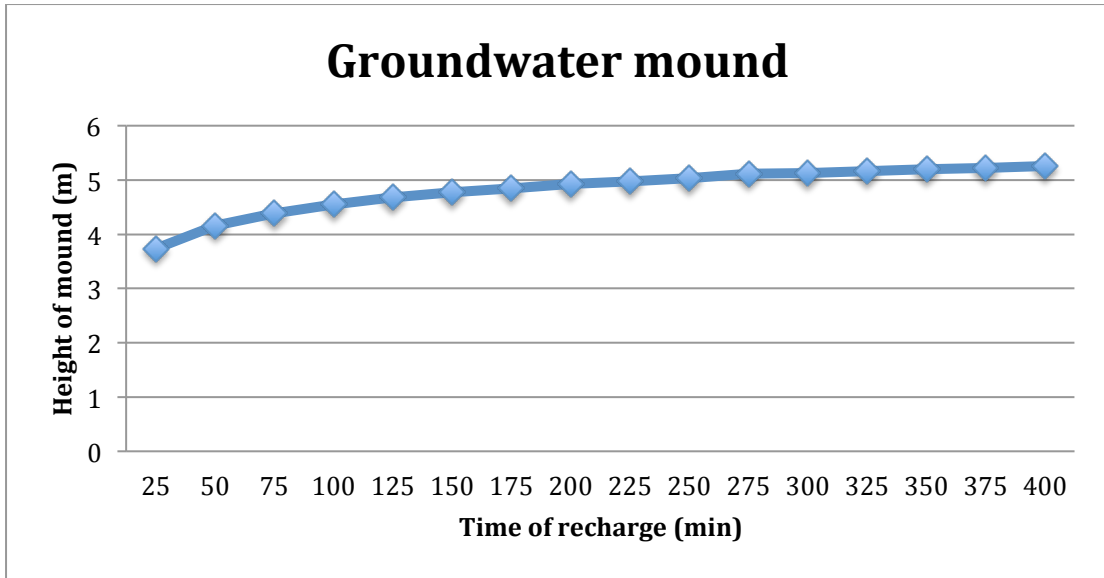
The infiltration gallery was designed and the design parameters are listed in the table below.

**Table 12:** Values of design parameters used in the design of infiltration gallery

S.No.	Design Parameter	Value
1	Diameter of the gallery	3.16 m
2	Total depth of the gallery	2.5 m
3	Depth of the gallery below pond	1.3 m
4	Infiltration rate	77.01 m <sup>3</sup> /hr
5	Mound height at the designed geometry	5.25 m
4	Capillary rise	0.246 m
5	Maximum allowable depth	3.75 m



**Figure 13:** Groundwater mound height with respect to distance at infiltration gallery



**Figure 14:** Groundwater mound height with respect to time at infiltration gallery

The protocols developed for the design of recharge systems in the present study can be applied to any case of urban and rural stormwater disposal problem, with the help of background information that can be easily acquired from municipal water supply department or local driller of bore-wells.

Use of infiltration well has been suggested for urban sub-watershed. This gives emphasis to time-based disposal of stormwater. Infiltration gallery has been suggested for the rural watersheds for volume-based disposal of stormwater. The infiltration gallery gives importance to volume of the stormwater.

The infiltration well was used at the urban sub-watershed of Civil lines, Patiala (Punjab) having an area of 31733 m<sup>2</sup>. The stormwater received is 343 m<sup>3</sup> for 35 mm (90-percentile) rainfall for 210 min of rain, which is infiltrated at a rate of 75.99 m<sup>3</sup>/hr in 4.5 hr.

The infiltration gallery was used at the rural sub-watershed of pond 2 of Chhapa village, distt. Barnala (Punjab) having an area of 151110 m<sup>2</sup>. The stormwater received is 505.71 m<sup>3</sup> in 35 min of 35 mm (90-percentile) rainfall, which is infiltrated at a rate of 77.01 m<sup>3</sup>/hr in 6.58 hr.

The recharge facilities designed herein are designed for unclogged conditions hence; the effective infiltration rate may be reduced due to clogging. Further, the untreated stormwater is not allowed to enter the recharge facility in any case.

Future work may involve the design of filters, consideration of effect of clogging by suspended solids and sludge of bio-solids, multi-permeable aquifer recharging and multiple aquifer recharging.

## GLOSSARY

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**Aquifer** A permeable geological formation or body that will yield water in economical amounts.

**Aquitard** A semipermeable geological formation or body that will retard the flow of water through it

**Capillary fringe** A zone above the water table where the soil is saturated but under tension (pressure less than atmospheric), as opposed to the zone below the water table where water is under pressure.

**Confined aquifer** An aquifer overlain by an impermeable layer such that the piezometric head rises above the top of the aquifer.

**Darcy's law** The relationship discovered by Henri Darcy between flow rate, hydraulic conductivity, and gradient in a porous medium.

**Groundwater** Water at or below the water table in earth materials.

**Hydraulic conductivity** The ease with which a fluid will flow through a porous medium. It is a function of the pore size and fluid properties of viscosity and density.

**Hydrogeology** is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust

**Hydrograph** A graph of flow rate of a stream versus time. It also refers to a graph of the water level in a well versus time.

**Hydrology** is the study of the movement, distribution, and quality of water

**Hydrometeorology** is a branch of meteorology and hydrology that studies the transfer of water and energy between the land surface and the lower atmosphere

**Infiltration capacity** The maximum rate at which a soil will allow water to infiltrate it from the surface. It is dependent upon the initial moisture content of the soil, the vertical hydraulic gradient, and the rate of precipitation.

**Permeability** The property of a porous medium to transmit water. It is a function of pore diameter.

**Physiography** is that branch of natural science which deals with the study of processes and patterns in the natural environment

**Porosity** The percent ratio of void volume to total volume of a rock or soil.

**Sedimentary rock** A rock formed from the weathered products (detritus) of igneous, metamorphic, or other sedimentary rocks (e.g., sandstone, siltstone, shale).

**Specific storage** The volume of water that will be obtained from a unit volume of aquifer upon release of a unit value of head.

**Specific yield** The ratio of the volume of water drained from a soil to the total matrix volume.

**Stormwater runoff** is unfiltered water that reaches streams, lakes, sounds, and oceans by means of flowing across impervious surfaces.

**Unconfined aquifer** An aquifer that has no overlying confining impermeable layer.

**Up-flow roughing filter** Roughing filters are often used to pretreat water by removing suspended solids from the water that could rapidly clog a slow sand filter. Filters operating in up-flow direction.

**Vadoze zone** is the part of Earth between the land surface and the top of the phreatic zone i.e. the position at which the groundwater (the water in the soil's pores) is at atmospheric pressure

## REFERENCES

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1. Anderson, J. G. (2007). *Assessment of Stormwater Best Management Practices*. Retrieved July 11, 2007, from [wrc.umn.edu/outreach/stormwater/bmpassessment/assessmentmanual/index.html](http://wrc.umn.edu/outreach/stormwater/bmpassessment/assessmentmanual/index.html)
2. Arora A. S., Reddy A.S. (2012). Multivariate analysis for assessing the quality of stormwater from different Urban surfaces of the Patiala city, Punjab (India). *Urban Water Journal*.
3. ASCE Standard. (2001). *Standard guidelines for artificial recharge of groundwater*. Environmental and water resources institute, American Society of Civil Engineers. ASCE Standard.
4. Barnett, S. R., Howles, S., Martin, R. R., Gerges, N. Z. (2001). *Aquifer Storage and recharge: innovation in water resources management*.
5. Batchelor, G. (1967). *An Introduction To Fluid Dynamics*. Cambridge University Press.
6. Bear, J. (1979). *Hydraulics of Groundwater*. New York: McGraw-Hill.
7. Bouwer, H. (1999). *Artificial Recharge Of Groundwater: Systems, Design, And Management*. McGraw-Hill.
8. Bouwer, H. (2002). Artificial recharge of groundwater: hydrogeology and engineering. *Hydrodeology Journal* (10), 121-142.
9. Central Ground Water Board. (2011). *Select Case Studies: Rainwater Harvesting and Artificial Recharge*. Ministry of Water Resources. New Delhi: Central Ground Water Board.

10. CGWB. (2007). *Manual on Artificial Recharge of Groundwater*. Ministry of Water Resources. Government of India.
11. D'Oria, M., Tanda, M., Zanini, A. (2008). Flood Water storage as a resource for agriculture and groundwater recharge: the emptying of artificial leaking ponds. *American Geophysical Union, Fall Meeting*.
12. Daniel, T. (2008). *An Adaptive Decision Support System for Urban Stormwater Management*. IWA Publishers, Royaume Uni.
13. Dendrou S., Dendrou B. (1999). *Contaminant Transport in the Unsaturated Zone*. Boca Raton: CRC Press LLC.
14. Dhakad, S. S., Agrawal V. (2009). Tube Well recharge techniques in vertisol of Raisen district of M.P. *International Journal of Agricultural Engineering*, 2, 228-230.
15. Domenico, P. A., Schwartz F. W. (1990). *Physical and Chemical Hydrogeology*. New York: John Wiley & Sons.
16. Draft Green Infrastructure Supplemental Stormwater Document. (2009). *Stormwater Design and Specification Manual*. Indianapolis: City of Indianapolis Green Infrastructure.
17. Drost, B. G. (1998). *Hydrology and Quality of Groundwater in Northern Thurston County*. Washington: U. S. Geological Survey Water- Resources Investigations Report 92-4109.
18. Ferguson, B. K. (1990). Role of the Long-term Water Balance in Management of Storm Water Infiltration. *Journal of Environmental Management*, 30, 221-233.
19. Fetter Jr, C. W. (1980). *Applied Hydrogeology*. Columbus: Charles E. Merrill Publishing.

20. Flint A. L., Ellet K. M. (2004). The Role of the Unsaturated Zone in Artificial Recharge at San Gorgonio Pass, California. *Vadose Zone Journal*.
21. Hantush, M. (1967). Growth and decay of groundwater-mounds in response to uniform percolation. *Water Resources Research*, 3 (1), 227-234.
22. Hatt B. E., Deletic A., Fletcher T. D. (2006). Integrated treatment and recycling of stormwater: a review of Australian practice. *Journal of Environmental Management*, 102-113.
23. Heath, R. (1983). Basic ground-water hydrology. *U.S. Geological Survey Water-Supply Paper* (2220), 86.
24. Horsley Witten Group, Inc. (2010). *Rhode Island Stormwater Design and Installation Standards Manual*. Rhode Island Department of Environmental Management. Rhode Island: Coastal Resources Management Council.
25. Jha M. K., Kamii Y., Chikamori K. (2008). Cost-effective Approaches for Sustainable Groundwater Management in Alluvial Aquifer Systems. *Springer Science*.
26. Lim C. H., Lim N. S. (1999). Urban stormwater collection for potable use. *Water Supply Journal*, 503-509.
27. Lohman, S. (1972). *Ground-Water Hydraulics*. Washington: U.S. Geological Survey.
28. Maestre A., Robert P., Morquecho R. (2005). *The National Stormwater Quality Database*. The University of Alabama, Tuscaloosa, Department of Civil and Environmental Engineering. Washington, D.C.: U.S. EPA, Office of Water.
29. Massmann, J. W. (2003). A Design Manual for Sizing Infiltration Ponds. *WA-RD* (578.2).

30. Massmann, J. W. (2003). *A Design Manual for Sizing Infiltration Ponds*. Department of Transportation. Washington: Washington State Transportation Commission.
31. Morris D. A., Johnson A. I. (1967). Summary of hydrologic and physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey. *U.S. Geological Survey Water-Supply Paper* , 1839-D, 42.
32. Raju, K. C. (1998). Importance of Recharging Depleted Aquifers: State of the Art of Artificial Recharge in India. (pp. 429-454). *J. Goel Soc. India*, 51.
33. Reid R. C., Prausnitz J. M., Sherwood T. K. (1987). *The Properties of Liquids and Gases* (4th ed.). Ney York: Mc-Graw Hill.
34. Singh L., Ravichandran S. (2011). Studies on Estimative Methods and their Role in Artificial Ground Water Recharge. *International Journal of ChemTech Research*, 435-440.
35. Siriwardene N.R., Deletic A., Fletcher T.D. (2007). Clogging of stormwater gravel infiltration systems and filters: Insights from a laboratory study. *Water Resource Journal*, 41 (7), 1433-1440.
36. Theis, C. V. (1935). The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Am. Geophys. Union Trans*, 16, 519-524.
37. Todd, D. (1980). *Groundwater Hydrology* (2nd Edition ed.). New York: John Wiley & Sons.
38. Vermont Agency of Natural Resources. (2002). *Vermont Stormwater Management Manual*.
39. Water Planning Division, USEPA. (1983). *Nationwide Urban Runoff Program*.

USEPA.

40. Winiarski T., Bedell J. P., Delolme C., Perrodin Y. (2006). The impact of stormwater on a soil profile in an infiltration basin. *Hydrogeology Journal*, 14, 1244-1251.