STORMWATER MANAGEMENT IN URBAN LAHORE FOR GROUNDWATER RECHARGE UNDER EXTREME RAINFALL EVENTS

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ABSTRACT: Over the last few decades, the metropolitan of Lahore has changed drastically with expansion of urbanization towards the east and south but also changed the typical character of urbanization. In particular, the drainage network has been outdated by this growth and hence the flow obstructions create ponding conditions under severe storm events. Due to increase in population, groundwater abstraction is also at increase which resulted in decline in water table of Lahore aquifer. The mechanism to be adopted would recommend dampening the extreme storm runoff and the utilization of the diverted flows in recharging the aquifer. To do so it was necessary to identify those areas that have potential for drainage carriers and also have adequate space available for recharge mechanism having and urban land use ratio between 1.2-2.75. The study focused on possibly generated extreme storm water from 10-year extreme rainfall event to recommend areas for recharge mechanism implementation across the urban land. A Dem of 2.5 m elevation has been used in order to apply a delineation processing and number of catchments have been identified along with their natural drainage network. Historical extreme rainfall events have been identified to drive a process for hydrograph generation given with peak discharges at some ponding locations. A sample catchment has been selected to calculate flood ponding capacity and number of recharge wells that can utilize the open space in order to augment ground water of Lahore aquifer. Considering minimum required spacing amongst the recharge wells, a total of 09 recharge wells could be installed per ha of open space which equates to a maximum installation of 288 wells within the 32 ha of space that would correspond to maximum recharge potential of 0.13 Mm^3.

Keyword: Groundwater recharge, urbanization, stormwater management, catchment delineation, extreme rainfall events.

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INTRODUCTION

Lahore is the capital of Punjab province and the second largest city in Pakistan. It is located on the world map with geographical coordinates as: 31° 32′ 58″ N and 74° 20′ 36″ E with its proximity to Kasur district in the South and Sheikhupura in the North-west. Figure 1 is showing location of study area.

Population density varies from urban to rural areas of Lahore. Center of the Lahore is denser than newly built up housing societies ranging from 1000 persons per hectare to 150 persons per hectare respectively. Mazhar and Jamal (2009) stated that within a time span, population projection is based on certain assumptions regarding development of major components of change in population.

Mahmood *et al*. (2011) indicated that in Lahore rapid increase in population, industrialization and urbanization are cause of increase in water supply demand. In order to fulfil fresh water demand, overpopulation is leading the aquifer towards irreversible water table depleting situation.

Niemczynowicz (1999) has defined that due to increase of urban population, new sources of water necessary to satisfy growing water demand are increasingly difficult to find and utilize. Overexploitation of fresh water has resulted in deep extraction and water depth reached more than 50 meters (155amsl) in center of the Lahore city as shown in Figure 2. Basharat and Rizvi (2011) also stated that Lahore is a big metropolitan where access to clean drinking water is a survival issue with an ever increasing population.

Mahmood *et al*. (2011) mentioned that Lahore is a sub-tropical, semi-arid region. The average annual rainfall is recorded as 629 mm (24.7 in) while average monsoon rainfall is 470 mm (18.5 in). Generally, monsoon rainfall causes runoff in urban and rural areas of Lahore district that can be used wisely to replenish ground water. Annual maximum daily rainfall data (from 1957 to 2014) is shown in Figure 3.

Miguez *et al*. (2012) Identified that there is a need to employ various engineering and science disciplines in order to consider all parts of urban water cycle which ensure social, economic, environmental and ecological sustainability, because sustainable criteria for urban drainage has become a greater challenge.

The drainage network of Lahore originally consisted of storm water drains with proper catchments draining directly in the drains. However, with population increase and enhanced construction activities the drainage areas were deformed and a few reaches of areas flow directly into the drains. With passage of time the sewage flow has increased much and the storm water along with sewage is pumped into the drains. As such, the original storm water drains have now become sewage drains. Figure 4 shows drainage network of Lahore with major drains.

Jafarzadeh *et al*. (2018) stated that rainfall induced runoff, and resulting urban flooding is one major problem of the communities, as well as industrial and urban centers. The flow obstructions create ponding conditions under severe storm events that are not mitigated through gravity means and require on-site forced drainage. It is in these topographic depressions where rainwater accumulates as shown in Figure 5.

Due to inadequacy of the existing drainage system some of the depressed locations in thickly populated and commercial areas in Lahore have become sore points. Water from these ponding prone areas either has to be pumped out or allowed to soak into the ground through ponding for several hours of stagnation.

Accordingly, there exists a need to isolate a mechanism that can foresee the excess storm water drainage requirement in a manner best suited to the local constraints and preferably to utilize the diverted flows in rejuvenating the aquifer system.

MATERIAL AND METHODS

Data Collection and Analysis: Rainfall data has been collected from Pakistan Meteorological Department (PMD) from year 1957-2014 and the historical annual maximum daily rainfall pattern of Lahore city. Based on annual maximum daily rainfall data of Lahore spanning 58 years (from 1957 to 2014), there are 5-6 extreme rainfall events with average value of 200 mm as shown in Figure 6.

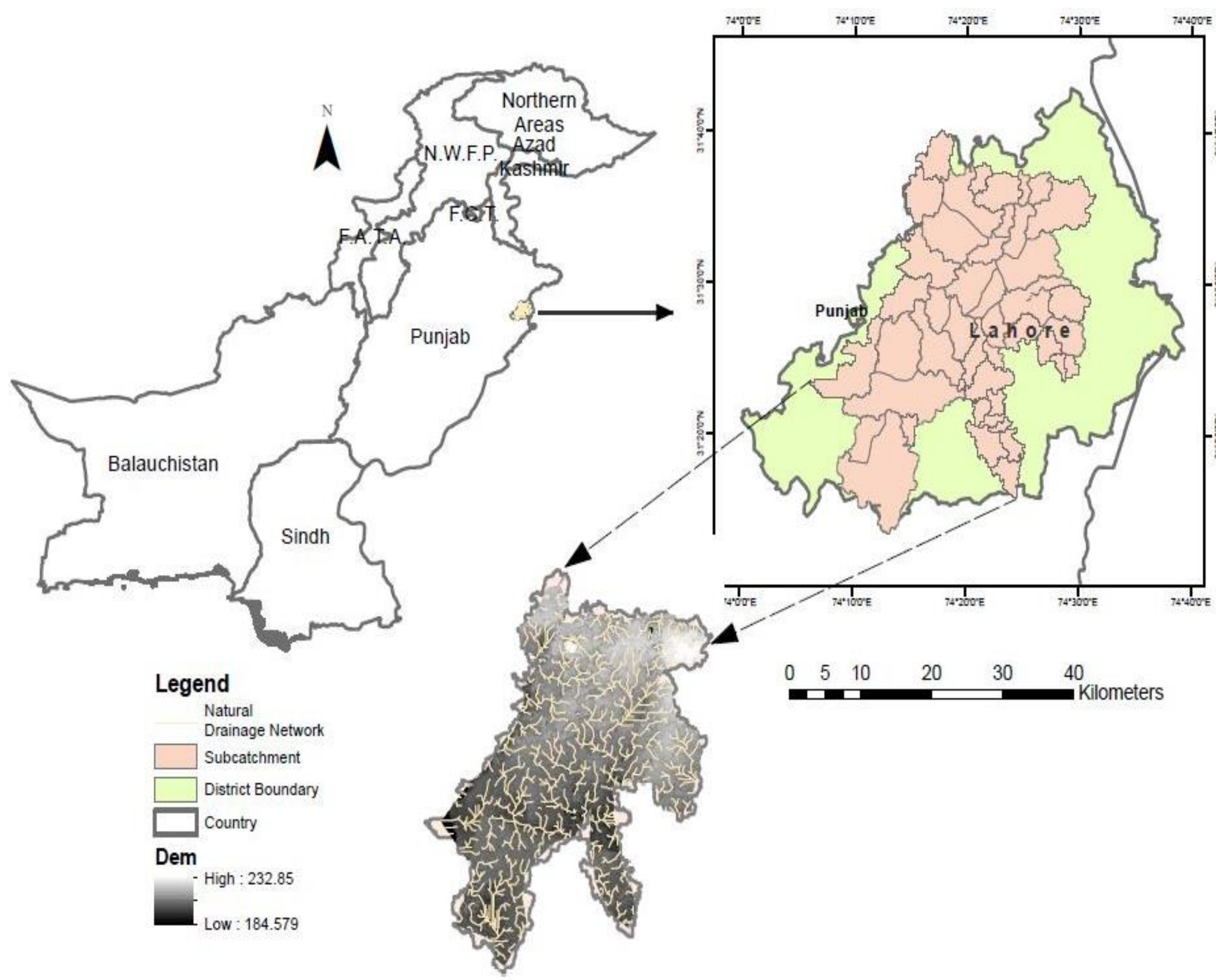

Figure 1. Map of Study Area

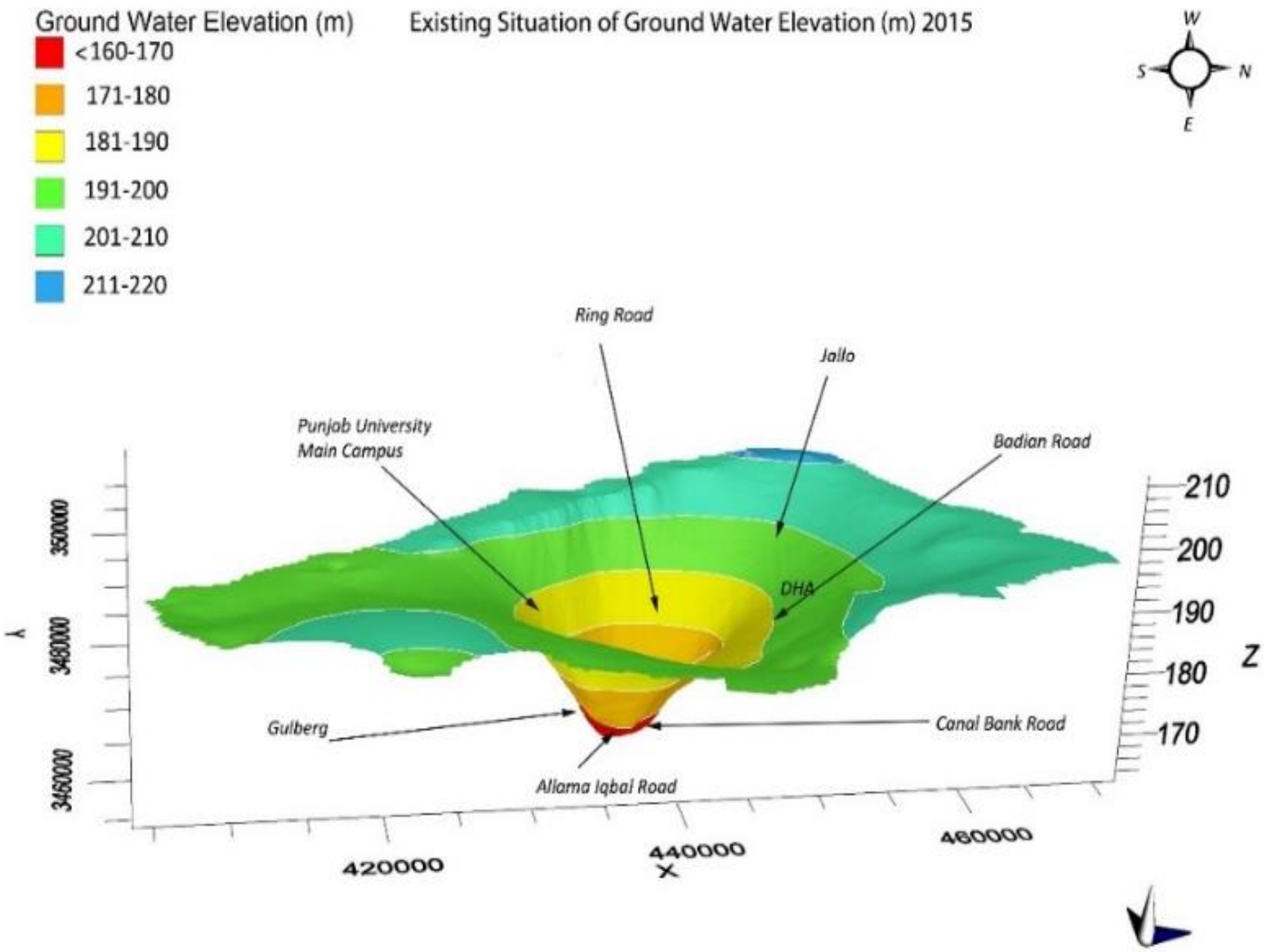

Figure 2. Current Situation of Ground Water Level (amsl)

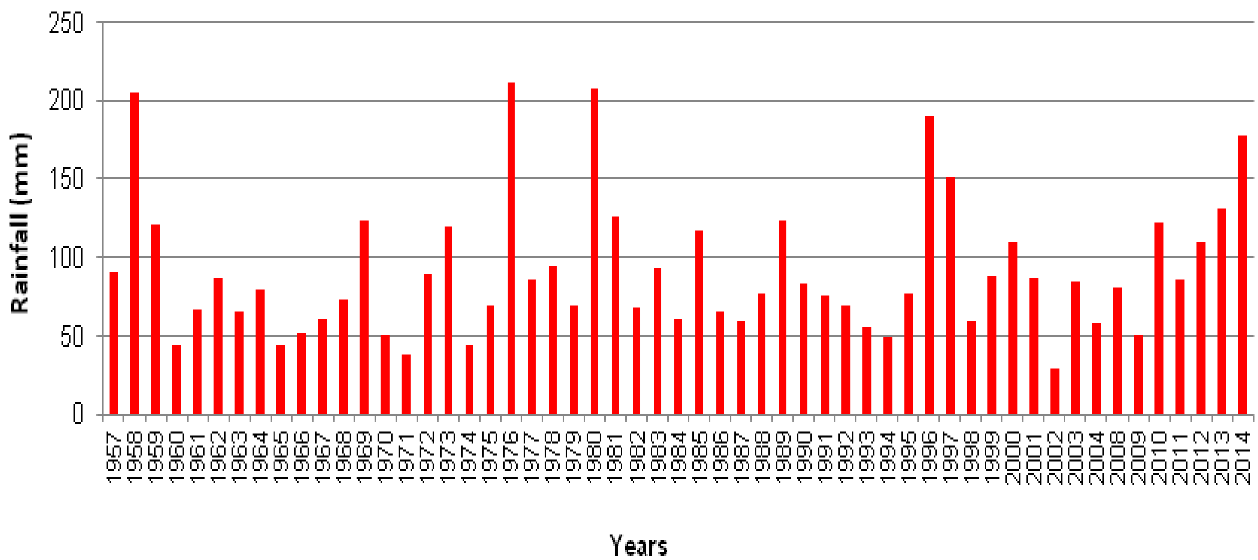

Figure 3. Annual Maximum Daily Rainfall of Lahore (Source: Metrological Department Lahore)

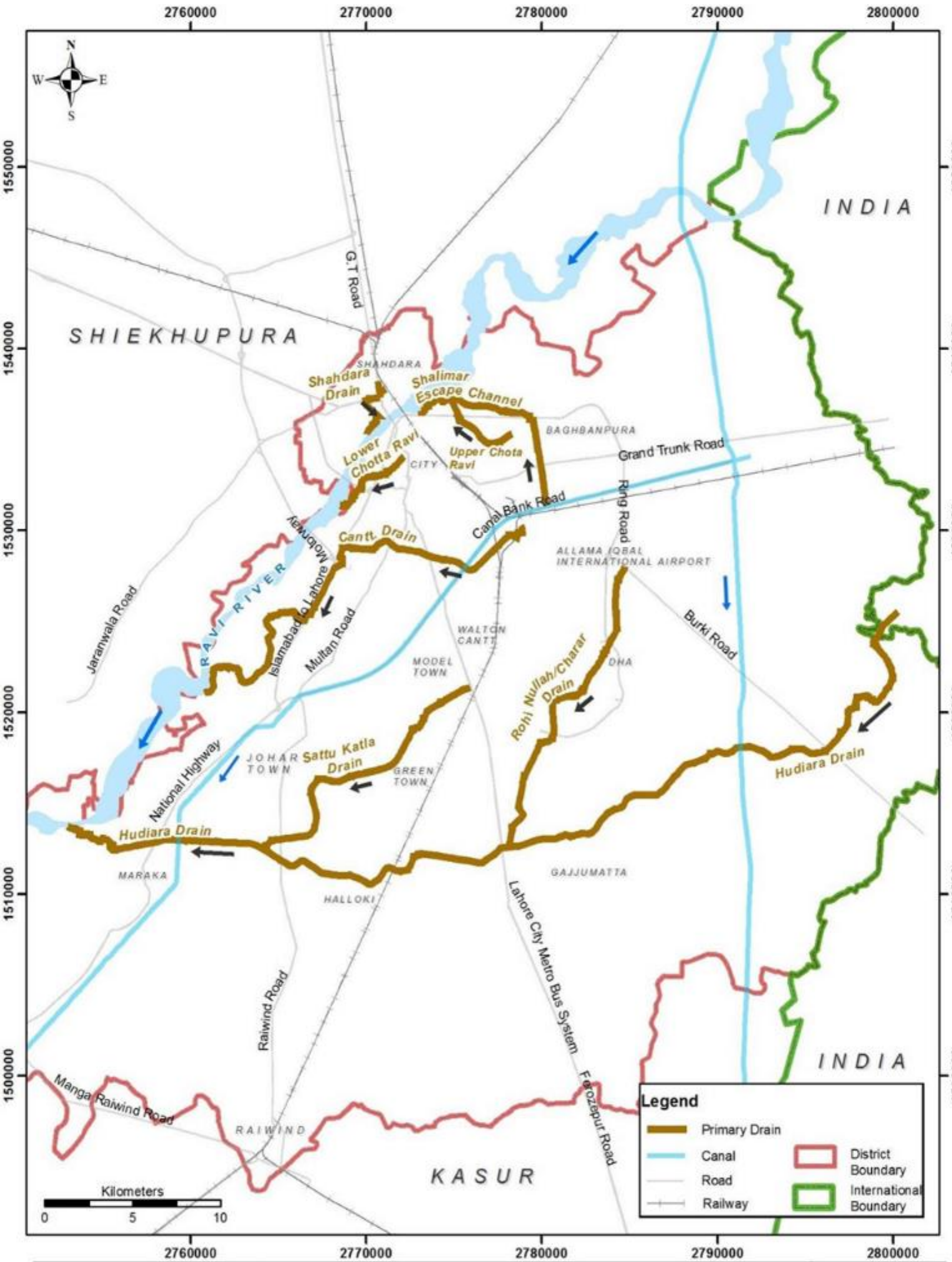

Figure 4. Drainage Network of Lahore (Source: MM Pakistan, (Pvt) Ltd.)

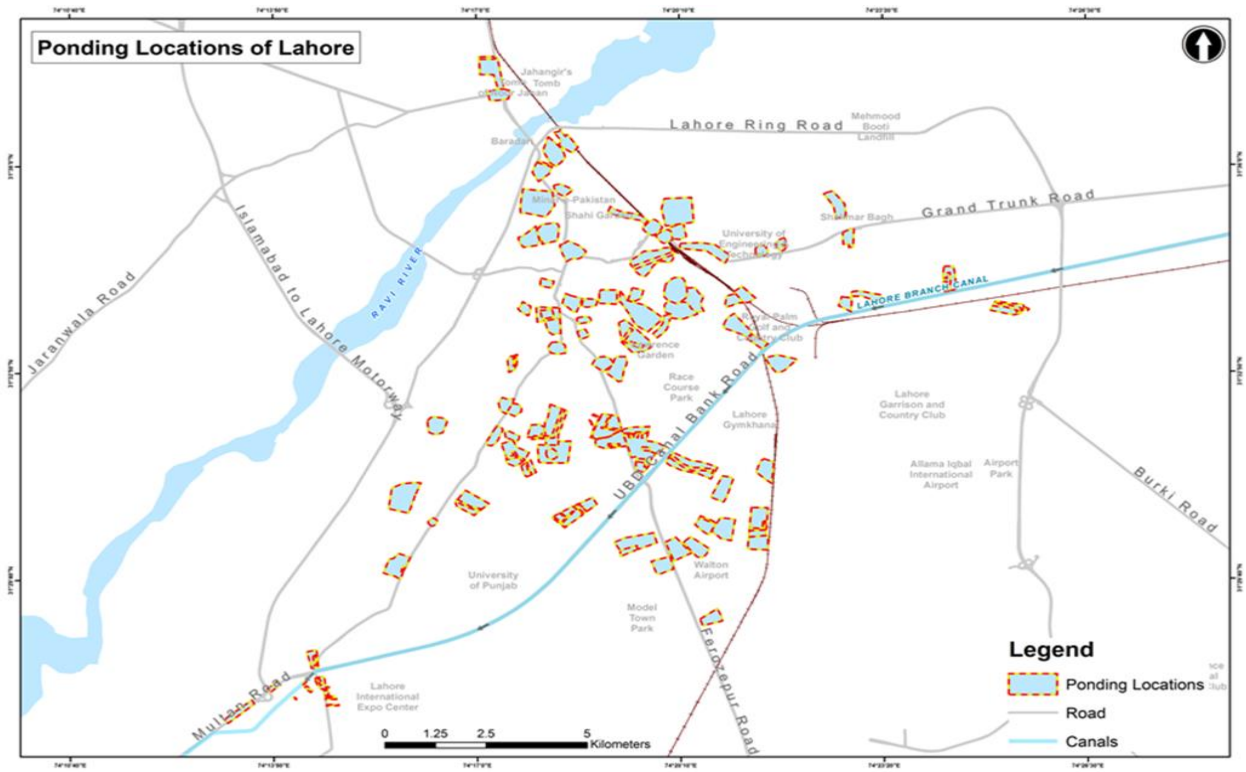

Figure 5 Critical Ponding Locations in Lahore (Source: MM Pakistan, (Pvt) Ltd.)

MATERIAL AND METHODS

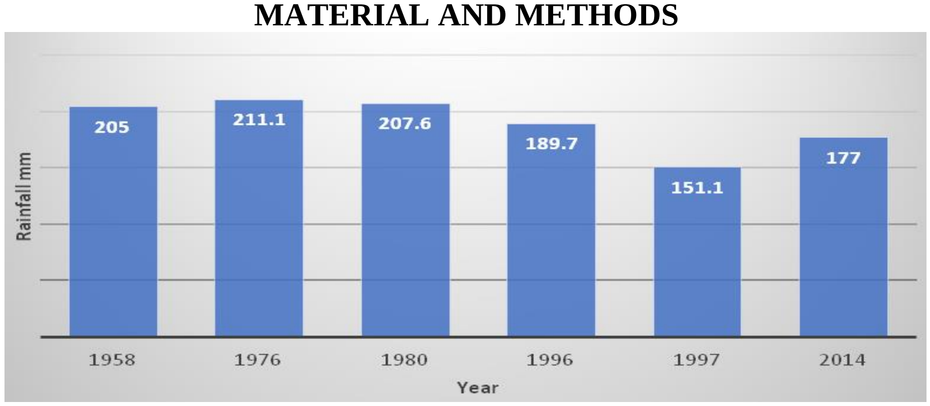

Figure 6. Extreme Rainfall Events

Data related to existing drainage network and water table has been collected form Water and Sanitation Authority Lahore (WASA) and Department of Land Reclamation (DLR). Characteristics of existing drainage network are given in Table 1 and Figure 7.

Table 1. Characteristics of Drains within Urban Lahore (Source: MM Pakistan, (Pvt) Ltd.)

Sr. No.	Drains	Length (km)	Catchment Area (ha)	Capacity (Cusec)
1	Sattu Katla	17	13,277	800
2	Upper Chotta Ravi	3.3	1,537	1480
3	Lower Chotta Ravi	3.5	666	500
4	Shalimar Escape Channel	5.03	2,829	300
5	Shahdara Drain	4.02	1,040	260
6	Cantt Drain	19.4	10,120	900
7	Charar Drain/Rohi Nullah Drain	18.3	62,39	800

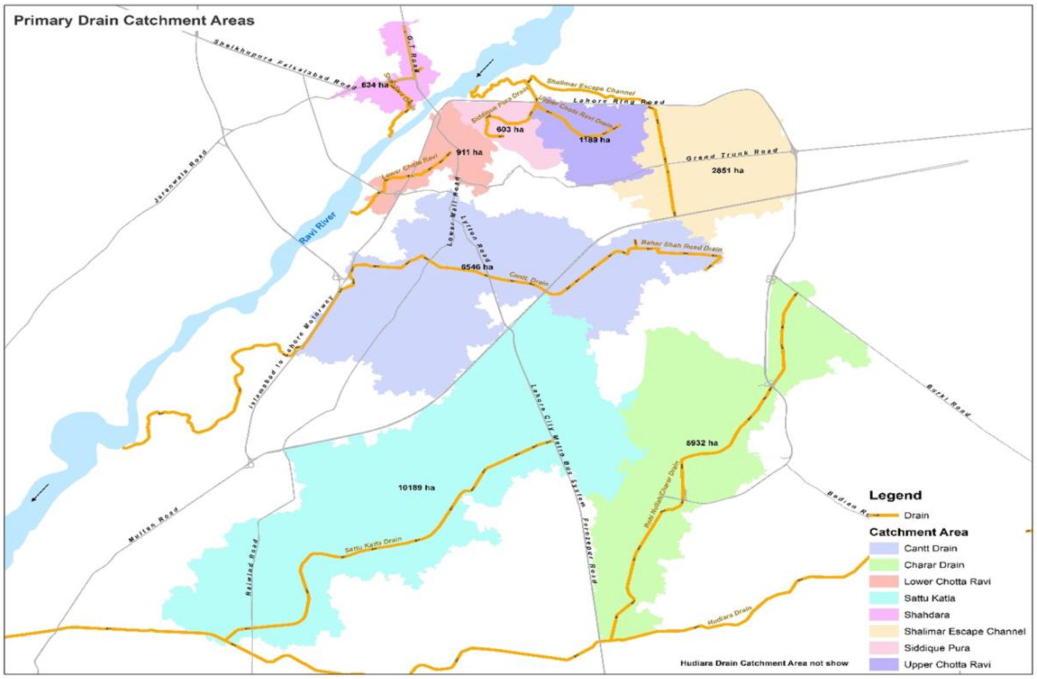

Figure 7. Catchment Area of Primary Drainage (Source: Water and Sanitation Authority)

Strategic Choices: Given approach is not about common infrastructure adjustments that are adopted to cater typical magnitudes of flow, rather it would provide better solutions to dampen the impact of possible peak flows from 10-year return period rainfall and to utilize the remaining discharge in recharging the aquifer of Lahore to some extent.

Holman-Dodds *et al*. (2003) indicated that as an alternative approach by maintaining traditional engineered stormwater infrastructure, it may possible to recharge local ground water aquifer in addition to reducing amount of surface runoff. In order to achieve the above intervention, engineering plans for storm water capture of the surplus runoff volume need to be devised by means of recharge wells.

Mechanism of recharge is mainly dependent on the type of land available in urban area. This would require determination of percentage of open and built up area available in each sub catchment of the urban environment so as to utilize it for establishing recharge mechanism to augment ground water.

Components to Define: There are three basic components for establishing an approach for storm water management of Lahore restricted to only urban premises. For the execution of this approach, mapping of these major components such as (i) hydrological assessment of urban Lahore, (ii) available land use classification and (iii) existing urban drainage network delineation is required. The individuality of these components is combined to produce the assessment for the attenuation in storm water flows through the (iv) recharge mechanism. Detail about these components is given below.

The respective primary drainage catchments as previously shown in Figure 4 are internally made up of sub-catchments defined by their stream flow patterns and constituting areas varying in size from 115-8,655 ha, as shown in Table 2. Zope *et al*. (2015) indicated that estimation of flood hydrograph, flood peak, time to flood peak and flood plain delineation are very important for the effective flood management in an urban area. Delineation of these urban area catchments is due to processing of digital elevation model data. For this analysis, 2.5 m ground resolution data has been used that can provide surface contour intervals between 2-3 m. Akram *et al*. (2012) explained that it is essential to delineate a watershed into smaller areas where variables can be considered similar due to spatial and temporal variations of that watershed.

Part of the management strategy for urban extreme flow events recognized the percentage of land constitution in terms of the ratio of built-up versus open areas. Classification of landuse leads to determination of suitability of open space targeted for storm water flow dissipation and proposing recharge wells. Catchments with low urban runoff potential have higher percentage of open space than built-up areas. These catchments allow higher infiltration of runoff. Similar situation is for areas under settlement expansion where open spaces are being acquired by infrastructure development.

Pitt and Clark (2008) stated that selecting storm-water controls based on an understanding of the problems in local receiving waters that result from runoff discharges is emphasis of sustainable storm-water management. Individual hydrological catchments and their flows have been derived on the basis of procedure illustrated in Figure 8. Comparative flow volumes that would be generated in sample sub-catchment as a result of variable storm event return periods of 2, 5 and 10-years. Satheeshkumar *et al*. (2017) indicated that significant constitute the sources of water for recharge of ground water in the watershed are rainfall and runoff. Primary and major source of recharge into the ground water is rainfall. While runoff in any watershed is affected by geomorphological factors basically land use change affects the volume and rate of significantly.

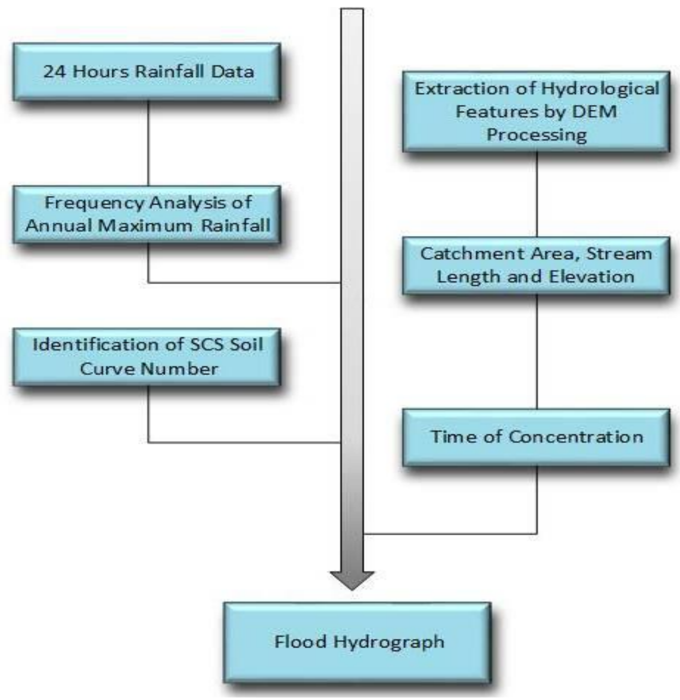

Figure 8. Procedural Steps for Flood Hydrograph

Assuming 30% of utilization of open spaces, engineering interventions would seek the design to route and utilize the divertible flows to recharge wells. This would be one and above the mechanism to cater to the disposal of surface flows through the existing system of open spaces. Pratima *et al*. (2011) defined that artificial recharge to replenish groundwater aquifer through surface waters is the planned engineering system of human interventions that can augment groundwater amount available for abstraction. A portion of landuse in each of the sub-catchment can be utilized to implement engineering practices in order to dampen the impact of extreme floods and recharge the aquifer to available potential. Pratima *et al*. (2011) has used the analytical approach, that is the modification of Darcy's seepage flow equation by which a well's recharge capacity can be estimated. The Recharging Flow (Q_r) in bore well by constant head recharge is calculated using **Error! Reference source not found.**.

$$\boldsymbol{Q_r = 2.75 * d * H * K}$$

Equation 1

Where,
d = Diameter of bore (m),
H = Depth of pervious sand strata (depth maximum 20m below groundwater level (m) and
K = Coefficient of Permeability (m/hr),

$$Q_r = 2.75 * d * 20 * K$$
$$Q_r = 55 * d * K\ (m^3/hr)$$

The equation for 'Q_r' shows that recharge rate of well directly proportional to with diameter of bore and coefficient of permeability. The recharge rate is extremely changed with small variation in aquifer permeability. With known permeability of aquifer proper diameter (d) of well can be adopted. If higher design of recharge is required, then larger diameter of bore hole will be used.

RESULTS AND DISCUSSION

Pratima *et al*. (2011) stated that method of artificial recharge to groundwater should be given preference by everyone in urban areas. Rainwater collected in everyone's roof top or property can be taken in to account to for availability regarding replenishment of aquifer. Catchments with still higher concentration of urban structures generate runoff that is of maximum concern when planning for urban stormwater flows. Here, maximum municipal interventions would be required to offset the damaging impact of flooding. On the other hand, there are some catchments that have potential to serve as rainfall harvesting areas with limited open spaces available. Dourte *et al*. (2013) higher intensity of rainfall patterns is cause of higher rate of runoff that can be infiltrated to groundwater for recharge purpose.

The classifier (ratio of built up area to open spaces) calculated for sub-catchments is as follows:

- Low Urban Runoff Potential with buildup vs. open space ratio <0.8
- Area Under Development with ratio of 0.8-1.2
- Area having Potential for Runoff Carriers with ratio of 1.2-2.75
- Rainfall Harvesting Areas with ratio of >2.75

The service areas of respective sub-catchments in terms of previous classifier are depicted in Figure 9 and Table 2. Given the targeted concerns of our study, it becomes necessary to identify those areas that have potential for drainage carriers and also have adequate space available for recharge mechanism under ratio of 1.2-2.75. It is in these areas where storm water management strategy with recharge mechanism, if adopted, lends itself to efficient mitigation. Such areas, as serviced by their existing primary carrier drains are listed in Table 1. Against a 30% utilization of open space, the net available space for recharge appears in Table 3.

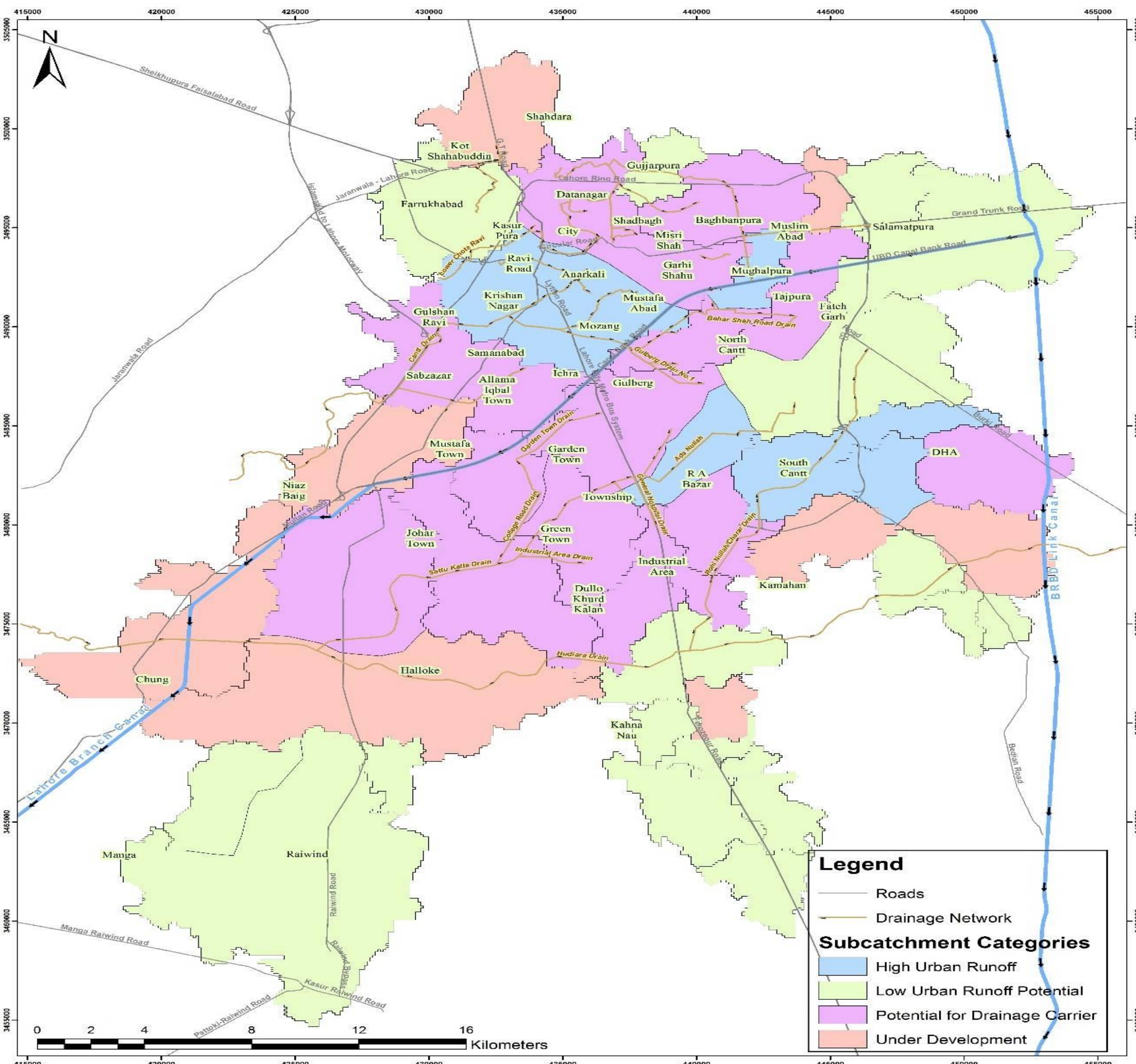

Figure 9 Sub-catchments Classified for Urban Land Use Ratio within Urban Lahore.

Table 2. Classifier for the Landuse of Urban Lahore.

Catchment Area (ha)	Built-up (ha)	Open Space/Agricultural (ha)	Classifier Ratio	
1139.1	138.7	1000.4	0.14	
866.0	198.3	667.7	0.30	
2691.1	643.0	2048.1	0.31	
411.0	102.3	308.7	0.33	
584.0	150.1	433.9	0.35	
980.2	299.2	681.0	0.44	
8655.1	2675.9	5979.2	0.45	
419.0	133.9	285.2	0.47	
4344.2	1428.3	2915.9	0.49	**Low Urban Runoff Potential**
426.0	142.0	284.0	0.50	
282.0	99.0	183.0	0.54	
1637.4	577.7	1059.7	0.55	
2454.1	886.3	1567.8	0.57	
610.0	233.3	376.7	0.62	
3939.1	1508.4	2430.7	0.62	
1964.1	760.7	1203.4	0.63	
714.0	282.2	431.9	0.65	
609.0	274.1	335.0	0.82	
520.8	239.5	281.4	0.85	
1988.1	947.6	1040.5	0.91	
1748.0	845.6	902.4	0.94	
4141.2	2030.0	2111.2	0.96	**Under Development**
6700.3	3355.5	3344.8	1.00	
1429.1	725.2	703.9	1.03	
2371.1	1274.7	1096.4	1.16	
115.0	62.1	52.9	1.17	
1980.9	1116.5	864.4	1.29	
1409.1	813.2	595.9	1.36	
3258.2	1957.5	1300.6	1.51	
1217.8	789.9	427.9	1.85	
1582.2	1039.8	542.3	1.92	
3507.5	2326.3	1181.2	1.97	
2168.1	1455.9	712.2	2.04	**Potential for Drainage Carriers**
2024.9	1367.5	657.4	2.08	
4106.2	2799.0	1307.2	2.14	
1445.8	993.8	452.0	2.20	
2670.6	1851.7	818.8	2.26	
3290.6	2368.8	921.8	2.57	
1941.1	1413.9	527.2	2.68	
1334.1	986.7	347.5	2.84	
3244.1	2441.5	802.6	3.04	**High Urban Runoff Potential**
4007.7	3337.7	670.0	4.98	
667.3	566.1	101.2	5.60	

Extreme Storm Event Volumes: Figure 10 below not only shows the areas of the sub-catchments consistent with Table 2 but also provides calculation of the potential run-off volume for each sub-catchment that would be generated as a result of a 10 year return period storm event which for urban Lahore is an extreme case.

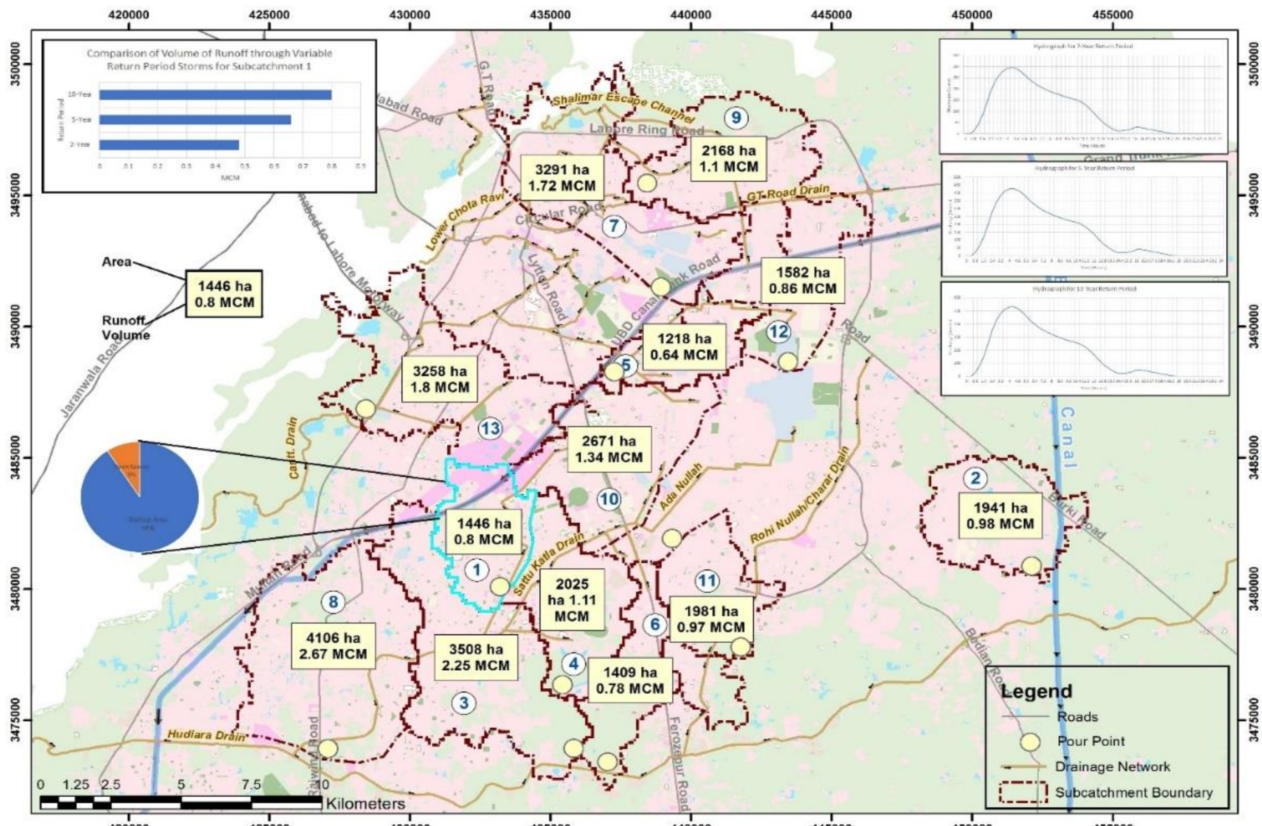

Figure 10. Distribution of Sub-catchments with Potential for Drainage Carriers

Table 3. Net available Space for Recharge within Sub-catchments with Potential for Recharge Mechanism.

Catchment No.	Builtup (ha)	Open Space (ha)	30% of Open Space (ha)
1	1313	133	40
2	1376	565	169.5
3	1623	1885	565.5
4	1508	517	155.1
5	1140	78	23.4
6	874	535	160.5
7	2815	476	142.8
8	3141	965	289.5
9	1584	584	175.2
10	2433	238	71.4
11	1357	624	187.2
12	1271	311	93.3
13	2605	653	195.9

Sample Sub-catchment: Towards ease of analysis bearing on management of stormwater flows from extreme events, the evaluation has focused on a sample urban catchment shown as sub-catchment 1 in Figure 11. A comparison of volume of runoff generated from variable return periods such as 2-year, 5-year and 10-year for Sub-catchment 1 is also shown with subsequent unit hydrograph peaks of 297, 429 and 531 cusecs. Total area of sub-catchment 1 is 1,446 ha comprising 91% built-up area and remaining in open spaces. College Road Drain, a secondary drain and associated tertiary drains carry the runoff towards primary drain (Sattu Katla) which has the capacity to discharge peak flow of 990 cusecs. Total volume of runoff generated is about 0.8 Mm^3 for the 10-year return period.

Comparison of extreme flow generated through 2, 5 and 10-year return period for a catchment is shown in Figure 11. Out of total 1,446 ha of catchment area, 91 percent is built up area and remaining is open space. Identification of pour points based on natural network of streams lead to quantification of runoff generated on each network nodal point for the 10-year return period. Volume of runoff generated in the catchment is drained from College Road as secondary drain and associated tertiary network and eventually into the primary carrier Sattu Katla drain which has the capacity to discharge peak flow of 990 cusecs.

For adopted soil permeability of 1.0 m/hr and well diameter of 0.61 m, calculated recharge rate of a well is 34.0 m^3/hr. Considering minimum required spacing amongst the recharge wells, a total of 09 recharge wells could be installed per ha of open space which equates to a maximum installation of 288 wells within the 32 ha of space that would correspond to maximum recharge potential of 0.13 Mm^3. This compares with maximum run-off of 0.8 Mm^3 against 10-yr return period flows.

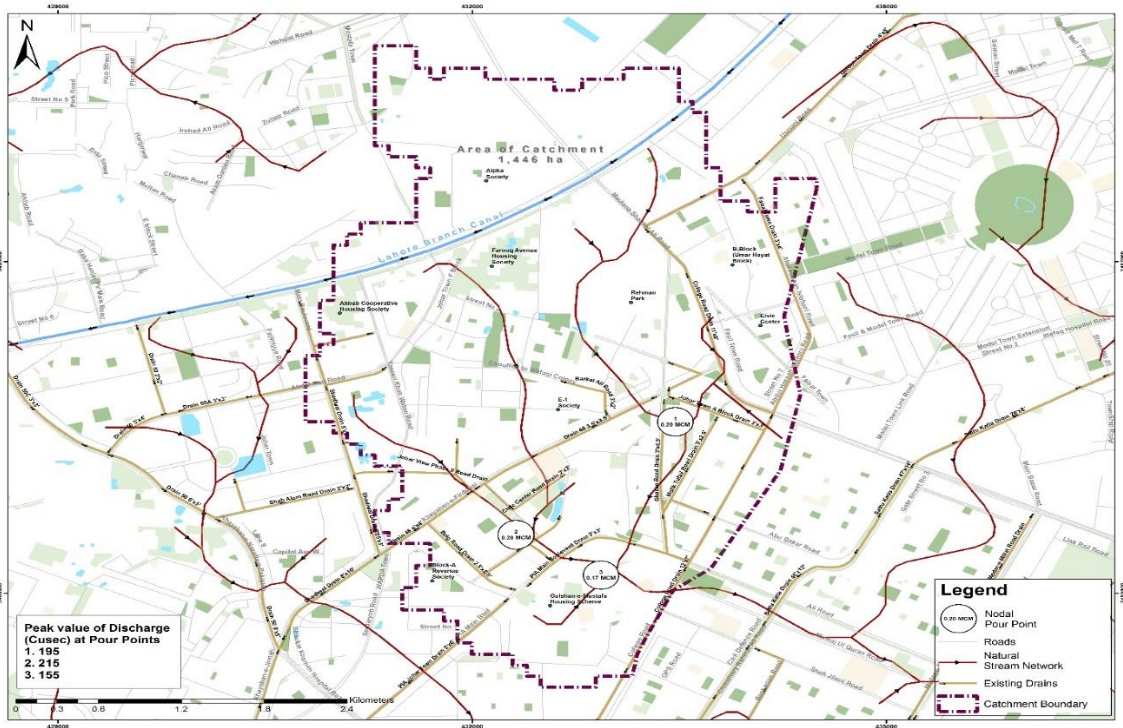

Figure 11. Estimation of Peak Discharge for Natural Drainage Pour Points under Sample Sub-catchment 1.

Conclusion: Lahore represents one of the largest metropolitan areas within Pakistan with ranking increase in urbanization because of overpopulation and sprawl of settlements. Putra and Baier (2008) stated that in cities of developing countries, urbanization and population pressure are two main challenges to water resource management. This study is part of an exercise to dampen the impact of extreme flows that could possibly be generated from 10-year extreme rainfall event to recommend areas for recharge mechanism implementation across the urban land. Accordingly, this study has examined possibilities for stormwater dissipation against the following objectives:

- Dampen the impact of urban flooding
- Re-routing of the flood waters
- Estimation of recharge potential

Ferguson (1990) explained that the main management focus is the increase in the peak rate of stormwater runoff that is due to the introduction of impervious area. Groundwater can be recharged potentially by artificial infiltration of urban stormwater which can also sustain stream base flows in addition to improving stormwater quality and contribute to flood control. For a given sub-catchment, one representative area was chosen for interventions accompanied by planning and engineering calculations for stormwater flow mitigation. The given process that can be easily replicated for other sub-catchments and it is flexible enough to accommodate higher peaks resulting from extreme events assuming land is available in sub-catchments as highlighted in Table 2.

Part of the management strategy for urban extreme flow events recognizes the percentage of land constitution in terms of open and buildup areas. Given the targeted concerns of the study, it becomes necessary to identify those areas that have potential for drainage carriers and also have adequate space available for recharge mechanism having and urban land use ratio between 1.2-2.75, as shown in Table 2.

Akther *et al*. (2010) stated that to protect future water quality and quantity to fulfill future demands, the aquifer requires sustainable management. The conclusion provides the strategy as a practical model of infrastructure-oriented adjustments. Based on extreme rainfall events, it has led to engineering interventions within the sample sub-catchment 1 to capture runoff at street level and to route the surplus flows towards proposed recharge sites.

REFERENCES

Akram, F., M. Rasul, M.M.K. Khan, and M.S.I.I. Amir (2012). Automatic Delineation of Drainage Networks and Catchments using DEM data and GIS Capabilities: A case study. Paper presented at the 18th Australasian Fluid Mechanics Conference Launceston, Australia.

Akther, H., M.S. Ahmad, and K.B.S. Rasheed (2010). Spatial and temporal analysis of groundwater level fluctuation in Dhaka City, Bangladesh. Asian Journal of Earth Sciences, 3(4), 222-230.

Basharat, M., and S.A. Rizvi (2011). Groundwater Extraction And Waste Water Disposal Regulation–Is Lahore Aquifer At Stake With As Usual Approach? Pakistan Engineering Congress, World Water Day, Lahore (pp. 112-134).

Dourte, D., S. Shukla, P. Singh, and D. Haman (2013). Rainfall intensity-duration-frequency relationships for Andhra Pradesh, India: changing rainfall patterns and implications for runoff and groundwater recharge. Journal of hydrologic Engineering, 18(3), 324-330.

Ferguson, B. K. (1990). Role of the long-term water balance in management of stormwater infiltration. Journal of Environmental Management, 30(3), 221-233.

Holman-Dodds, J. K., A.A. Bradley, and K.W. Potter (2003). Evaluation of Hydrologic Benefits Of Infiltration Based Urban Storm Water Management 1. JAWRA Journal of the American Water Resources Association, 39(1), 205-215.

Jafarzadeh, M. S., K. Ostad-Ali-Askari, S. Eslamian, V.P. Singh, N.R. Dalezions and M.R. Etebarian (2018). Water Management in Urban Watersheds. International Journal of Emerging Engineering Research and Technology Volume 6, Issue 2, 2018, PP 23-36

Mahmood, K., A.D. Rana, S. Tariq, S. Kanwal, R. Ali and A. Haider (2011). Groundwater levels susceptibility to degradation in Lahore metropolitan. depression, 150, 8-01.

Mazhar, F. and T. Jamal (2009). Temporal population growth of Lahore. Journal of Scientific Research, 39(1), 53-58.

Miguez, M., A. Verol. and P. Carneiro (2012). Sustainable drainage systems: an integrated approach, combining hydraulic engineering design, urban land control and river revitalisation aspects. Drainage systems,1.

Niemczynowicz, J. (1999). Urban hydrology and water management–present and future challenges. Urban water, 1(1), 1-14.

Pitt, R. and S.E. Clark (2008). Integrated storm-water management for watershed sustainability. Journal of Irrigation and Drainage Engineering, 134(5), 548-555.

Pratima, P., M.D. Desai. and J.A. Desai (2011). Evaluation of hydraulic conductivity for the estimation of artificial groundwater recharge rate. Middle East Journal of Scientific Research, 10(5), 638-646.

Putra, D. and K. Baier (2008). Impact of urbanization on groundwater recharge–the example of the Indonesian Million City Yogyakarta. Paper presented at the UN Habitat-United Nations Settlement Programs: Fourth session of the World Urban Forum, Nanjing, China, Documentations of Germany's Contribution to a Sustainable Urban Future.

Satheeshkumar, S., S. Venkateswaran. and R. Kanan (2017). Rainfall–runoff estimation using SCS–CN and GIS approach in the Pappiredipatti watershed of the Vaniyar sub basin, South India. Modeling Earth Systems and Environment, 3(1), 24.

Zope, P.E., T.I. Eldho. and V.Jothiprakash (2015). Impacts of urbanization on flooding of a coastal urban catchment: a case study of Mumbai City, India. Natural Hazards, 75(1), 887-908.