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Original Article

Modelling Pollutant Build-up of Fines for a Peri-Urban Region: A Case Study of Pune Metropolitan City, India

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Abstract *- This paper demonstrates the results of extensive field investigations of the build-up of fines on impermeable surfaces in a peri-urban region of Pune Metropolitan City, India, during the winter months. The build-up study was carried out in four different locations based on the varied land use type on concrete or bitumen surfaces. The build-up varies with various environmental and geographical characteristics & is an extremely dynamic process. The build-up was found to be highest in commercial followed by the developing land, residential and urban-rural localities, respectively. Taking into consideration total solids (TS) as prime factors for this analysis, the power equation showed the best fit of the build-up model. The field experiment's results showed that the build-up process is significantly location-specific; build-up rates vary mainly with road characteristics, road traffic volume, and land usage. The relations between the major prominent parameters of the influencing buildup and the coefficients were evaluated. The multiplication coefficient 'a' is positively co-related with sweeping frequency and percentage of residential area while negatively co-related with traffic volume. The coefficient 'b' is influenced by traffic volume, roughness index and surface type. The results provide a wider perspective into the particle build-up process and can be further taken up for wash-off model equation formulation. These interpretations will be helpful to decision-makers in the development of sustainable stormwater management practices.*

Keywords *- Pollutant Build-Up Models, Land-Use, Stormwater management, Principal component analyses.*

1. Introduction

Stormwater pollution plays a significant role in deteriorating urban water bodies. Unplanned development and rampant urbanisation have created an imbalance in urban hydrology due to increased impervious surfaces. Rapid urbanization adds to the diffused pollutants which have been identified as a main cause of stormwater pollution[1]. Generally, road and urban runoff pollution are divided into two phases, with pollutants building up on surfaces during dry weather and washing off from surfaces during rainy events[2]. The contaminants in stormwater runoff are deposited on urban impermeable surfaces during the antecedent dry period between rainfall episodes[3][4].

Particulate solids are acknowledged as the main contaminant deposited on impermeable surfaces and act as the major transporter of other pollutants [5][4]. To prevent pollution in urban receiving water ecosystems, the key focus should be eliminating particle pollution deposited on impermeable surfaces[6]. Therefore, it is essential to understand this build-up process for devising sustainable stormwater pollution mitigation methods.

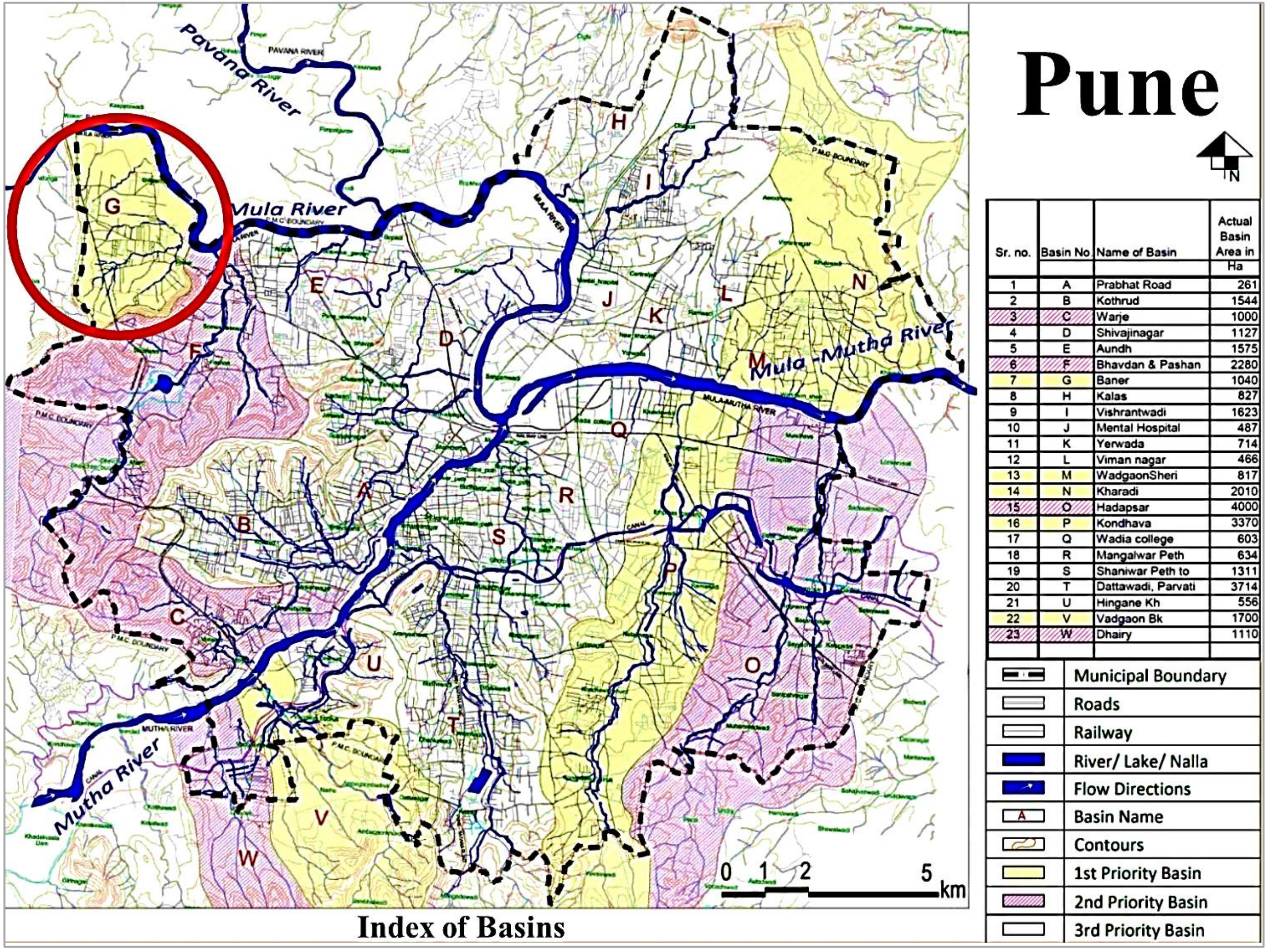
Various studies have identified factors that affect the pollution build-up on impervious surfaces. The previous studies identified the land-use type, climate condition, surface type, traffic volume, traffic density, the particle size of pollutant, sweeping frequency, and slope of the surface, initially as a factor that affects the trend of pollution build-up on the impervious surfaces[7]. The outcomes of the assessment of pollutant build-up on impermeable surfaces of "parking lot in Belgrade, Serbia" for the duration of the summer months exhibited that the contaminant accumulation was noticed to be larger on asphalt roads which bare major vehicular traffic than on concrete walkways[8]. As the build-up process is influenced by the redistribution of the accumulated particles due to anthropogenic and natural activities, the pollutant's particle size plays a significant role in particle accumulation on impervious surfaces. In a recent study, Wei noted the difference in the pollutant build-up process between coarser and finer particles [4]. Several researchers have attempted to use mathematical formulas to analyze the build-up process quantitatively. There are many standard equations[7][9], such as

- Reciprocal Form $y = a + \frac{b}{x}$
- Logarithmic form $y = a + b \ln x$
- Exponential form $y = ae - bx$
- Power form $y = \min(c, axb)$

Where: x = Antecedent Dry days
y = Build-up Load accumulated
a,b,c are coefficients

The power model represented the best fit for finer particle build-up [10][12][30]. Further studies are carried out to explore the significant, influential factors for the fine particle size fractions where the model performed satisfactorily. Then, an attempt is made to comprehend the interactions between these determining variables and the build-up model coefficients [4]. According to Sartor and Boyd (1972), numerous factors, including land use, topographical location, traffic volume & characteristics, and practices in municipal public works, influence the constituents found on street surfaces[13]. Furthermore, Gunawardana et al. observed that road dust predominantly comprises (60%) of soil from the surrounding region, implying that the previous area is a substantial source of particles[14]. The fundamental features of a catchment, both natural and built, such as landscape and land use characteristics, site characteristics, and particular anthropogenic activities, influence stormwater quality. Multivariate techniques were performed to explore associations between build-up coefficients and prominent factors.

A substantial extent of research work is done to understand the build-up process in developed countries' urban areas. However, there is a lack of understanding of how the build-up process behaves in the mixed urban catchment in developing countries. The prime objective of this study was to understand the formation of pollutant build-up on paved urban surfaces in a peri-urban area—the research aimed at collecting and evaluating particles below 75 µm. Further, the study identifies the factors affecting the pollution build-up process on impervious surfaces. To the author's notice, this study is the first attempt to develop a build-up equation for a city in India. Its results will be important in devising stormwater pollution mitigation strategies in the country.



Sr. no.	Basin No.	Name of Basin	Actual Basin Area in Ha
1	A	Prabhat Road	261
2	B	Kothrud	1544
3	C	Warje	1000
4	D	Shivajinagar	1127
5	E	Aundh	1575
6	F	Bhavdan & Pashan	2280
7	G	Baner	1040
8	H	Kalas	827
9	I	Vishrantwadi	1623
10	J	Mental Hospital	487
11	K	Yerwada	714
12	L	Viman nagar	466
13	M	WadgaonSheri	817
14	N	Kharadi	2010
15	O	Hadapsar	4000
16	P	Kondhava	3370
17	Q	Wadia college	603
18	R	Mangalwar Peth	634
19	S	Shaniwar Peth to	1311
20	T	Dattawadi, Parvati	3714
21	U	Hingane Kh	556
22	V	Vadgaon Bk	1700
23	W	Dhairy	1110

Source: Revised City Development Plan For Pune - 2041, Maharashtra, Under Jnnurm

Fig. 1 Pune basin map

Fig. 2 Location of the sampling spots in the study area for Build-up studies

2. Materials and Methods

2.1. Field investigations on the Peri-urban Region

The investigations were performed at four different locations in the peri-urban area of Pune city. Pune city is one the major city of western India, with high annual precipitation and increasing population density. The city is divided into 23 basins for stormwater management by the drainage department of Pune Municipal Corporation[15], the present study is conducted in the G basin of Pune City, as shown in Figure 1. Due to the rapid sprawl of industrialisation, a significant migration for livelihood purposes is observed. The study area has undergone rampant urbanisation and unplanned development. This resulted in a very dense mixed urban development with clusters of various land-use types, including residential, commercial, urban-rural (Gaothan area), developing land (under construction), etc. Unorganised unplanned growth is a typical trend observed on the peripherals of the cities in developing countries.

So it is extremely difficult to do zoning of the area according to its land-use type. Therefore, for this study, a mixed urban catchment of the G – basin in Pune is considered in the present study.

The four spots in the G- basin area, namely S1, S2, S3 and S4, according to their major land-use type, were selected as shown in Figure 2. The amount of each type of land use category within 0.2 km^2 of the circular region is estimated using the sample spot as the centre to determine the proportion of land use and also to determine roof area and road area percentages of previous land. [4].

Fig. 3 Sealed and unsealed roads

In the present study area, while choosing the sampling spot locations, it is observed that there are sealed and unsealed roads, as shown in Figure 3. The investigations were carried out only on sealed roads for the present study. The spots identified were on sealed roads where the stormwater grate inlets are present on the roadside. The S1 spot is identified as a residential area (86%) because its major area is covered by residential buildings having cement roads with medium traffic volume. Spot S2 is a commercial area (92%) consisting of a majority of IT parks and restaurants with cement roads but a very high traffic volume. Spot S3 is located in an under-construction area with heavily loaded trucks but low-frequency traffic volume on a cement road, typically representing a developing area (78%) of the G-basin. Spot S4 has located in an urban-rural (83%) (Gaothan) area, with a densely urbanised low-class urban setting, narrow bitumen road with low traffic volume, and high population density.

The sweeping is done manually by a broom on each spot once a day, usually in the early morning hours, whereas on the main road at the S2 spot, along with manual sweeping by broom, vacuuming is done once only to pick up big trash and plastic waste as shown in figure 4.

Fig. 4 Photographs showing manual sweeping and collecting the waste on the roadside and vacuuming for big trash/plastics on roads and footpaths

Fig. 5 Collection of dry accumulation using a vacuum cleaner

The agricultural land in this peri-urban area is minimal compared to the other land use, hence not considered in the present study. During the rainy season for the month of June and September, a video camera is placed to capture activity at the spots over the course of 48 hours. Data on traffic volume on weekdays and weekends are collected in each of these studies. The traffic volume is calculated based on the average values of the video observations for peak hours to fetch real-time traffic data. As per the IRC specification, the camber slope of cement and bituminous roads is measured and is in the range of 1.5-3[16]. The roughness index values were taken from Roughness Norms given in IRC: SP:16-2019 and were in the range of 2000-300 mm/Km[17].

2.2. Build-Up Sampling Procedure

The antecedent dry period is the key contributor to build-up accumulations on impermeable surfaces. Sartor et al. [13] investigated a build-up of up to 12 antecedent dry days, and Ball et al. [7] analyzed a build-up of up to 10 antecedent dry days [12].In the existing study, the investigation was carried out for 11 antecedent dry days at all four locations. For each antecedent dry day, two samples were collected. A build-up sampling process was majorly divided into two types of analysis, first for dry deposit accumulation and second for wet deposition sampling. Complexities due to the heterogeneous surfaces and their characteristics in urban areas contribute to pollutant loadings. The hypothesis that the characteristics are uniform across the small, constrained plot served as the basis for the study [18][4][19][12]. Therefore, a small plot of a 2m X 1.5m grid was selected for the present investigations. The frame was placed three fourth for the total distance between the median strip and the kerb. To carry out such investigations in urbanised areas in populated places, stopping the traffic at any moment in time was impossible.

Hence the selected site was more towards the kerb. The investigation of pollution build-up took place on one side of the identified road locations. All the sampling protocols were followed, and the tools used were washed with distilled water every time and dried appropriately. The vacuum machine was used to gather dry particulate pollutants from road plots, as depicted in Figure 5 [12]. To verify that all particulate material was captured, vacuuming was done three times in perpendicular directions[12]. Firstly, the dry dust sample was collected in a zipper pouch using a dry vacuum cleaner of 1200W. Based on previous research, the validity of using a vacuum system to collect pollutant samples has been demonstrated [2][20]. As conducted by Deletic et al., a calibration performed specifically for dry particulate samples for this study revealed an overall efficiency of 94% in collecting and retaining particulates and a minimum efficiency of 89% [18].

Secondly, deionised water was sprayed on the surface area until it got completely wet. This was done to allow to trap of the dissolved pollutants. The frames inside the surface were coated with hard plastic. A compressible rubber strip was used to line the bottom margins of the frame sides to seal the enclosed space, and weights were put on the sides of the frames to improve waterproofing. Deionized water was sprayed onto the road plot within the frame with the help of a commercially available spray chamber, which is frequently utilized for the application of pesticides. This exerted the right amount of pressure to remove the smaller silt particles without damaging the road's surface[18]. Spraying of the water on the test plot was done with the help of a sprayer, and care was taken to achieve uniform spraying over the entire plot. The wet deposition samples were collected using a suction pump with a power of 20kPa into the sampling bottles. The suction pipe was washed with distilled water to ensure minimal loss of particulate matter, with efficiency noted as 92%. Once it became clear from a tactile investigation that most of the silt had been swept out, the surface was cleaned and vacuumed repeatedly.

The wet samples were tested for Total solids (TS) Total suspended Solids (TSS), and Total dissolved Solids (TDS), in the laboratory as per the Indian Standard codes. For the present study, a relation between coefficients of build-up was identified for dry deposition and wet deposition samples. Samples passing through a 75-µm sieve were considered for further analysis for dry deposition. The total build-up load was found in g/m2 for both analyses.

2.3. Research Methodology

The purpose of the study was to develop a build-up model and investigate the influence of prominent factors on build-up development. The mathematical modelling of the accumulation of fine particles on the four selected sampling spots was the first step. The second step was to explore the significant, influential factors for the fine particle size fractions where the model performed satisfactorily. Following that, an attempt was made to determine the relationships between these key variables and the build-up model coefficients.

2.3.1. Governing Equation for the Build-Up of Fine Particles

The power equation represented the best fit for finer particle build-up [10][12][30]. As derived from Ball et. Al. [7] power model depicts a correlation between the build-up of pollutants and the preceding dry days (Eq. (1)).

$$B = aD{}^\wedge b \qquad (1)$$

Where,

B = the amount of fine particles build up on impervious surfaces per unit area (g/m^2);

a = the build-up rate coefficient (g/m^2 per day);

b = the coefficient that determines how rapidly build-up reaches equilibrium; and

D = the antecedent day period (day).

For simulating particle build-up, the power equation was converted into a linear, as given in Eq. (2), for regression analysis. [4].

$$Log(B) = Log(a) + b * Log(D) \qquad (2)$$

2.3.2. Analysing the Correlation Between Coefficients of the Build-Up Model and Influencing Factors

Multivariate techniques were performed to explore associations between build-up coefficients and prominent components. The principal component analysis (PCA) and multiple linear regression (MLR) techniques were used in this analysis. Principal component analysis, or PCA, has been employed for pattern recognition.

To find probable patterns or clusters between variables and objects, PCA reduces an array of raw data into a few significant elements that retain the greatest variance.[21]. Thus, significant, influential factors were identified. The type of association between the present parameters is determined using biplots. Each vector symbolises an independent parameter. The correlation shows an inverse relationship with the angle between the vectors. The connection strengthens with vector proximity. When two vectors are in opposition to one another, they are negatively linked. Uncorrelated vectors are those that are perpendicular to one another.

The derived regression coefficients were utilized to evaluate the influence of each component. According to Sartor and Boyd[30] (1972), numerous factors, including land use, topographical location, traffic volume and characteristics, and practices in municipal public works, influence the constituents found on street surfaces. Furthermore, Gunawardana et al. [19] observed that road dust is predominantly comprised of soil (60%) from the surrounding region, implying that the pervious area is a substantial source of particles. The catchment features, such as landscape and land use characteristics, site characteristics, and particular anthropogenic activities, influence stormwater quality and quantity [22][4][31].

In this study, the independent variables that govern the pollutants build-up were categorized into three groups: land usage (percentage of pervious area, roof area and road area);

characteristics of the site (Surface type, camber slope, roughness index); and anthropogenetic activities (sweeping frequency and traffic volume). Thus, the determining factors which impact the build-up coefficients (a and b) are represented in Eq. (3)[4].

Build−up coefficients = function of (land usage; characteristics of the site; anthropogenic activities) (3)

3. Results and Discussion

3.1. Analysis of Pollutant Build-Up for Finer Particles

The build-up load varied significantly in the four examined road spots. The main objective is to understand the varied nature of the attributes that contribute to the build-up. According to previous studies, the relationship between pollutant build-up and antecedent dry days can be represented using the power function [7][4][24], as in equation 1. From the literature, it is observed that pollution build-up is decreasing rate increasing function. The value of B is dependent on the variations in the value of ‘a’ and ‘b’, which are commonly regarded as build-up coefficients. The equations were confirmed by developing best-fit curves found using the least squares method.

The variations in the build-up were standardised prior to analysis. The process of standardizing involved dividing each data point by the highest possible build-up, named fraction build-up. It was considered, as it is assumed that the build-up for all four sites reached equilibrium at the end of each field investigation. [4] [25]. The derived coefficients of ‘a’ and ‘b’ are mentioned in Table 1 for finer particles. By minimising the sum of the squared errors between the simulated and experimental outcomes, the coefficients ‘a’ and ‘b’ were obtained. To assess the goodness of fit, R^2 and root mean square error for the total solids (TS) are given in Table 1. Figure 6 represents the fractional build-up fines for varied land use. The analysis of coefficients ‘a’ and ‘b’ are discussed in subsequent sections.

It is also observed in the study area, usually during dry climate conditions, although the main roads selected for this study are completely paved, the connecting sub-main roads have a dusty patch on both sides of the roads, favouring road dust resuspension. Traffic congestion and allied pollution on city roads are well-known facts and contribute to the finer particles.

Additionally, because there are low levels of vegetation or an open area next to these roads, extra quantities of dust are generated by the resuspension of urban soil. Manual sweeping with the hand broom is ineffective for handling such fine particles; hence, the intercept is seen in Figure 3 for all the spots.

Table 1. Values of build-up coefficients a and b for four sampling locations for finer particles

Site	a	b	R^2	Root Mean Square Error (RMSE)
S1(residential)	1.44	0.028	0.942	0.004
S2(commercial)	1.47	0.756	0.915	0.137
S3(developing)	1.65	0.29	0.915	0.052
S4(urban rural)	1.21	0.35	0.83	0.096

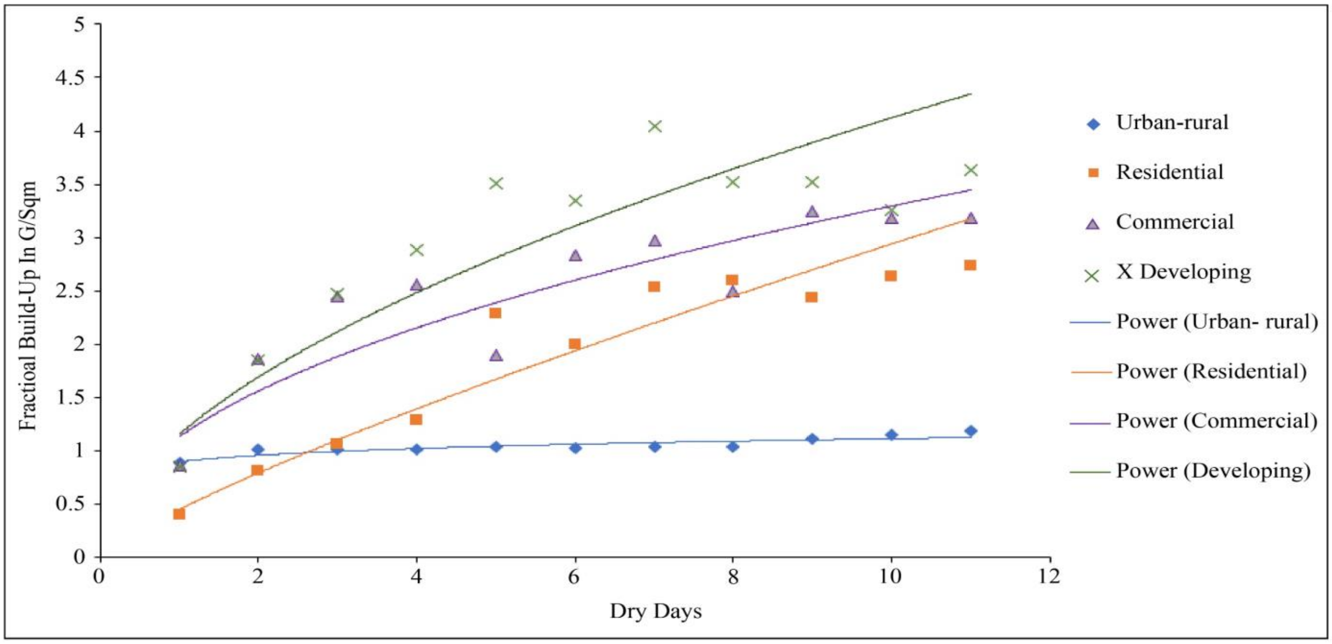


Fig. 6 Buildup of fines for varied land use

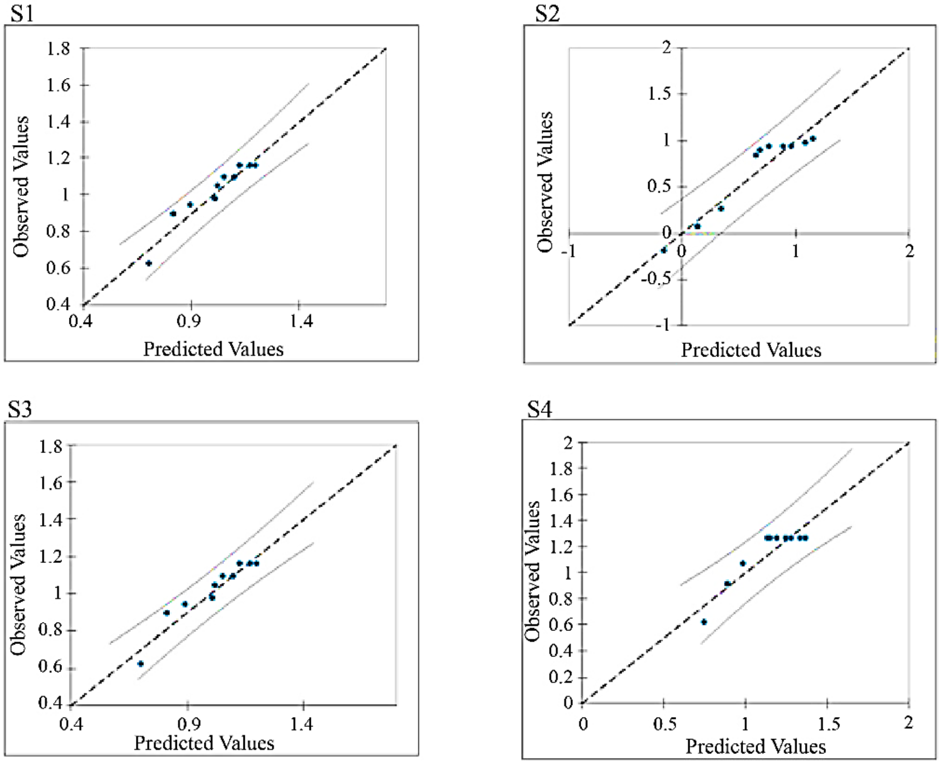


Fig. 7 Performance of the power model in predicting the buildup of fines

Figures 7 show the accuracy with which the power model functions in predicting build-up for size fractions less than 75 µm. The results of this study are best-fit for each of the four locations and lie within a confidence interval of 95%.

According to Liu et al. studies, the solids build-up estimates show a broad range of build-up characteristics even within the same land use. The reported variation of maximum build-up lies in the range (0.84-1.31 g/m^2) for residential, (0.55-1.22 g/m^2) for commercial and (1.12-4.40 g/m^2) for industrial land use[26]. The comparison with previous studies can be only possible if the site conditions are similar. The present study exhibits, the maximum build-up of fines for residential is 2.74 g/m^2, the commercial is 3.25 g/m^2, developing (under construction) area is 4.04 $g/m^{2,}$ For the urban-rural area, it is1.18 g/m^2 for fines, which is on the higher side may be because of typical site characteristics of the study area located on peripheral boundaries of the city.

3.2. Understanding Co-Relations for 'coefficient a'

As shown in Table 1, the coefficient a represents the multiplication factor, suggesting that it is coupled with particulates sources in the build-up. This multiplication coefficient was highest observed for S3 and lowest for S4.

The build-up coefficient for the developing area is highest may be attributed to the fact that the construction work is in progress. The removal of trash by vacuum cleaners, mainly on commercial roads, maybe the reason attributed to the moderate observed value. The coefficient 'a' was observed to be lowest in the urban-rural area, maybe because of narrow roads with less traffic volume. It is also noticed that the residents have the practice of sweeping and washing these bitumen roads in front of their houses, which can be the attributed reason.

Three primary components, F1 (40.7%), F2 (31.58%) and F3(27.7%), were obtained using PCA analysis. The PCA biplot between F1 and F2, accounting for 72.28%, is, as shown in Figure 8, shows that the build-up coefficient 'a' depicts positive relation with developing land and sweeping frequency but is negatively co-related with traffic volume. From the biplots between other principal components, i.e., between F1 and F3 and F2 and F3, it is observed that build-up coefficient 'a' is positively correlated with Roughness Index, Urban-rural location, percentage of road and residential area.

The coefficients derived from MLR as shown in Eq. (4). It was observed that MLR for 'coefficient a' the prediction error (0.00015) and R^2 (0.945), suggesting that the equation is satisfactory for quantitative prediction. From the equation, it is observed that the anthropogenic activities are accountable for multiplication coefficient a.

$$a_{fine} = 0.9982 - 0.00003323 * \text{Traffic Volume} + 0.4807 * \text{Sweeping Frequency} - 0.3958 * \text{Residential} \quad (4)$$

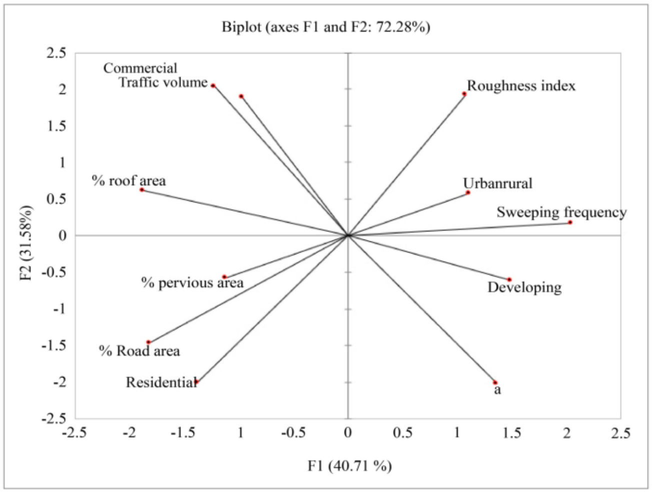


Fig. 8 **PCA biplots for first two components with 'coefficient a'**

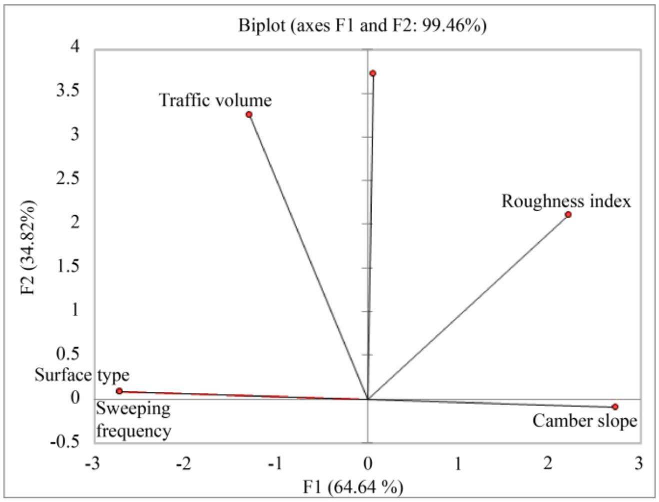


Fig. 9 **PCA biplots for first two components with 'coefficient b'**

3.3. Understanding co-relations for 'coefficient b'

Table 1 shows the coefficient 'b' value of fine particles for all the sites. Since the form of the pollutant build-up curve is influenced by the coefficient 'b', a higher value of 'b' suggests that the build-up curve takes longer to achieve equilibrium. In the present study, the coefficient 'b' implies that within the specified time, the S1 site first achieves the equilibrium, followed by S3, S4 and S2. The rate of particle redistribution determines how build-up will achieve equilibrium [27]. Particle resuspension is the starting point of the redistribution process. This occurs when external forces like traffic-stimulated turbulence reach a certain threshold value of surface stress [28]. Particle and road surface properties both have an impact on this process. This signifies that particle size and surface texture depth can influence particle re-suspension in addition to traffic and wind-driven forces [29]. The coefficient 'b' is lowest for residential areas, maybe as of low traffic density, whereas it is highest for the commercial area where the traffic density and traffic congestion are observed to be high. Thus given the scenario, anthropogenic activities (sweeping frequency and traffic volume) and site features (surface type, camber slope and roughness index) were identified as variables influencing coefficient b in this scenario. To establish the mathematical connection between coefficient b and its influencing components, the MLR analysis was conducted; Eq. (5) displays the resulting regression relationship.

$$b_{fine}=-1.113-0.00001467*TrafficVolume +0.007534*SurfaceType-0.0004866*Roughness\ Index \quad (5)$$

MLR for coefficient b was found to have a low relative prediction error (0.0003) and a high R^2 (0.98), indicating that the equation is trustworthy for quantitative prediction.

It was also noted that site characteristics dominate coefficient b. As noticed from equation 5, the site's characteristics are the primary contributors to an increase in equilibrium time, while traffic volume reduces equilibrium time due to a negative effect.

4. Conclusion

The build-up load varied significantly across four road locations during the field experiments. This suggested that the land use, traffic, and road surface characteristics of the build-up were diverse in nature.

Except for the residential site, where the build-up showed a small incremental increase with the ADD, a build-up was observed to be more for the first three days, and the increasing rate was low with the antecedent days. It is concluded that for fine particles (size<75 µ-m), the power equation exhibited a good fit.

The PCA biplots and regression models exhibited that build-up coefficient 'a' shows positive relation with developing area and sweeping frequency but is negatively co-related with traffic volume, whereas the coefficient 'b' showed a co-relation with traffic volume, roughness index and surface type. The coefficient a was dominated by anthropogenic factors, while b was influenced by site characteristics.

Further, this study can be taken up to understand the behaviour of the build-up of the coarser particulates. The pollutant build-up process is influenced by land usage, site characteristics and anthropogenic activities, and its prediction should be taken into due consideration by decision-makers for developing a strategy for sustainable stormwater management solutions.

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