Supplementary Material: Characterizing The Evolution Of Indian Cities Using Satellite Imagery And Open Street Maps

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Introduction

This document contains supplementary notes to the original paper titled "Characterizing The Evolution Of Indian Cities Using Satellite Imagery And Open Street Maps". The full paper has been accepted for publication in ACM COMPASS'20 [1]. This document includes a detailed explanation of several methods, and should be read in conjunction with the relevant sections of the paper.

Pixel-Level Error Correction: 3-Class Temporal Mapping

As described in Section-3, we need to identify for each pixel whether it remained constantly built-up (CBU) during 2016-2019, or constantly non-built-up (CNBU), or changed from non-built-up to built-up (Changed). To do this, we ran a 5x5 Gaussian convolution filter (sigma = 0.2; truncate = 11.0) on each pixel to obtain a value between [1, 25], and then tried to correct for errors by drawing a regression line on values across the four years. Figure-1 shows an example of two pixels, one of which remains constantly built-up and one which changes during these years. We can see that the Mean Squared Error (MSE) between the actual

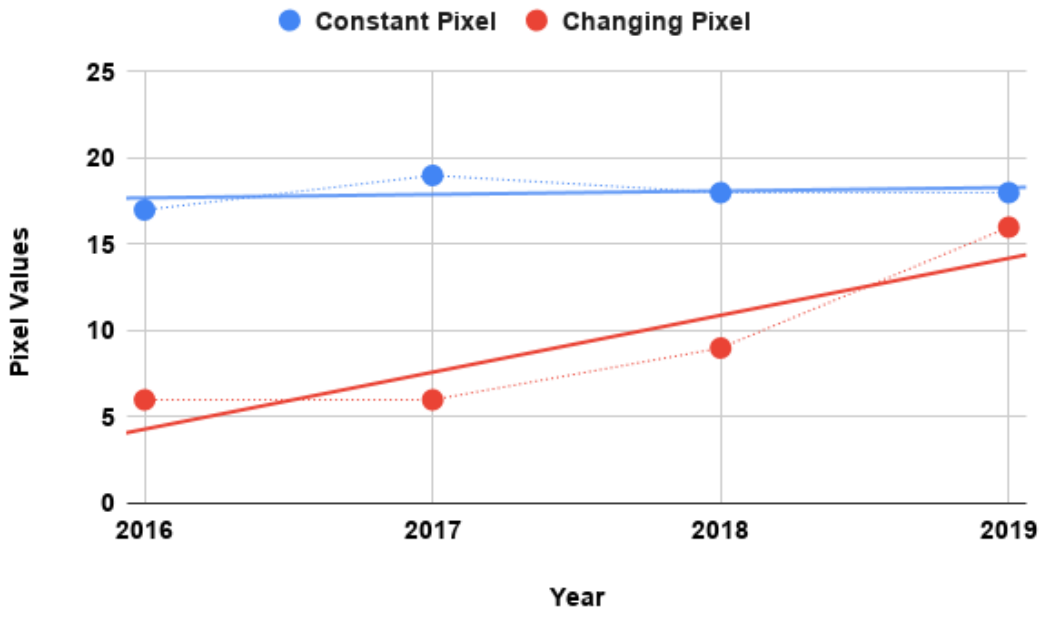


Figure (1) Regression line fitted to the pixel values across the years

values and regression values for CBU and CNBU pixels will tend to be lower than the mean square error for pixels that have changed. We determine a threshold on the MSE to classify pixels as CBU/CNBU or having changed between 2016 to 2019. To have a uniform method to determine the threshold for different districts, we draw a CDF plot of the MSE values of the pixels for each district, as shown in Figure 2.

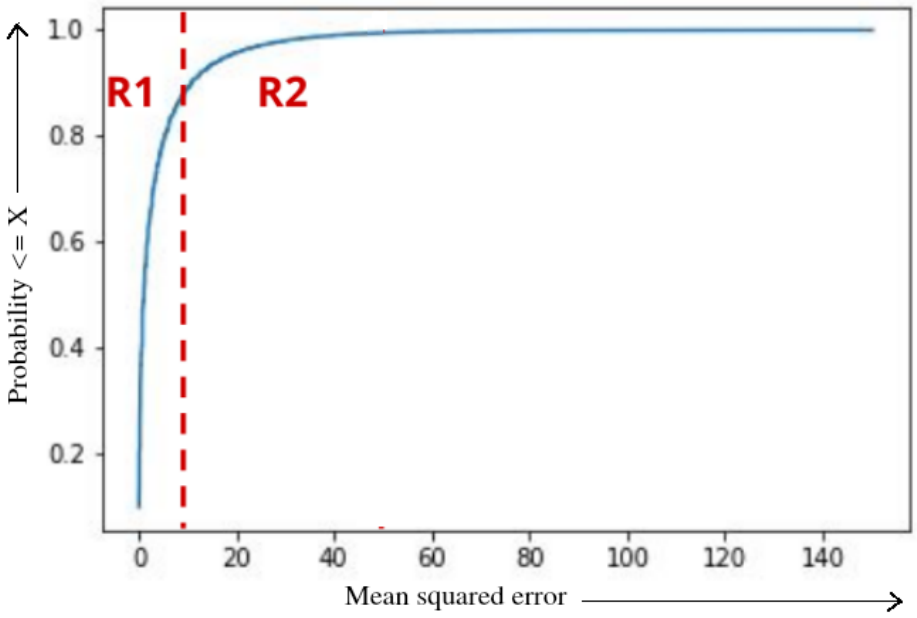


Figure (2) Thresholding on the CDF plot of MSE values

We found the CDFs for all the cities to have a similar characteristic shape. We then identify a knee point in the CDF when its derivative drops close to zero. This knee point thus divides the space into two regions, with the left-hand region containing CBU and CNBU pixels, and the right-hand region containing the Changed pixels. Table 1 shows the knee point threshold values used for each district.

City	Threshold Value
Bangalore	2.47
Chennai	2.95
Delhi	2.48
Gurgaon	2.47
Hyderabad	2.95
Kolkata	2.95
Mumbai	2.47

Table (1) City-wise threshold value for identifying constant and changing pixels between 2016 and 2019

Intra-City Transition Matrices For Urban, Peri-Urban And Rural Pixels

Table 2 shows the transition matrix for urban, peri-urban and rural pixels, between 2016 to 2019, for each city.

2016 | 2019	Rural	Peri-Urban	Urban
Rural	96.92	3.06	0.03
Peri-Urban	0	93.59	6.41
Urban	0	0	100

(a) Bangalore

2016 | 2019	Rural	Peri-Urban	Urban
Rural	87.38	12.29	0.33
Peri-Urban	0	92.28	7.72
Urban	0	0	100

(b) Chennai

2016 | 2019	Rural	Peri-Urban	Urban
Rural	94.86	5.05	0.09
Peri-Urban	0	93.44	6.56
Urban	0	0	100

(c) Delhi

2016 | 2019	Rural	Peri-Urban	Urban
Rural	98.62	1.38	0
Peri-Urban	0	95.94	4.06
Urban	0	0	100

(d) Gurgaon

2016 | 2019	Rural	Peri-Urban	Urban
Rural	77.55	20.24	2.21
Peri-Urban	0	88.64	11.36
Urban	0	0	100

(e) Hyderabad

2016 | 2019	Rural	Peri-Urban	Urban
Rural	68.65	30.7	0.66
Peri-Urban	0	95.5	4.5
Urban	0	0	100

(f) Kolkata

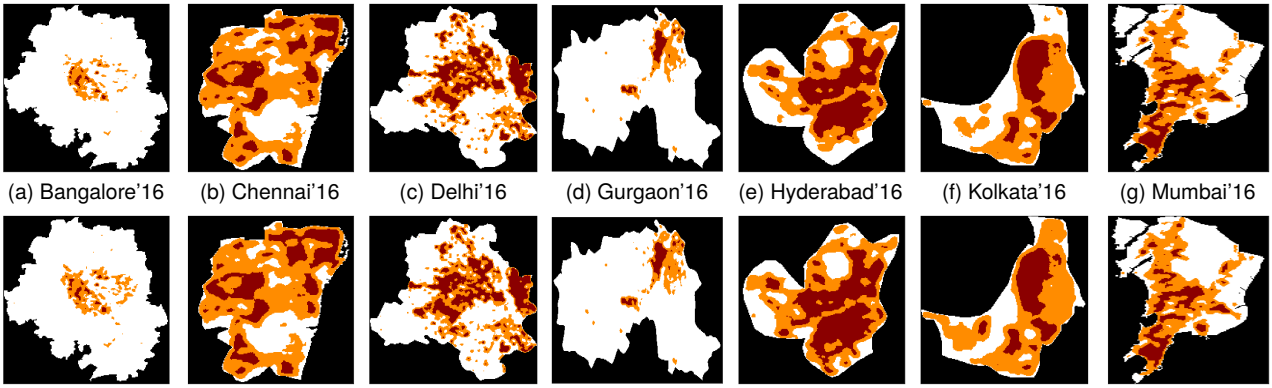
2016 | 2019	Rural	Peri-Urban	Urban
Rural	96.9	3.1	0.0
Peri-Urban	0	97.17	2.83
Urban	0	0	100

(g) Mumbai

Table (2) Intra-city transition matrices for urban, peri-urban, and rural pixels, between 2016 to 2019

Visualization Of The Urban Extent Of Cities In 2016 and 2019

Figure 3 shows the pixel-level classification of urban extent for the seven cities, in 2016 and 2019. Urban pixels are shown in red, peri-urban in orange and rural pixels in white. The blacked area lies outside the administrative boundaries of the districts. Table 3 shows the population and areas (in square kilometers) classified as rural, peri-urban, and urban areas in the seven cities. The population reported is as per the 2011 Indian census.



(a) Bangalore'16 (b) Chennai'16 (c) Delhi'16 (d) Gurgaon'16 (e) Hyderabad'16 (f) Kolkata'16 (g) Mumbai'16

(h) Bangalore'19 (i) Chennai'19 (j) Delhi'19 (k) Gurgaon'19 (l) Hyderabad'19 (m) Kolkata'19 (n) Mumbai'19

Figure (3) City-wise urban extent in 2016 and 2019

Intra-City Transition Matrices for C1-C5 Urban Grids

Table 4 shows the transition matrix for C1-C5 urban grids, between 2016 and 2019, for each city.

City	Population	Area (sq.km) in 2016			Area (sq.km) in 2019		
		Rural	Peri-urban	Urban	Rural	Peri-urban	Urban
Bangalore	8,443,675	2111.13	115.67	16.21	2046.07	172.76	24.18
Chennai	4,646,732	53.57	107.76	38.5	46.81	106.02	46.99
Delhi	11,034,555	1043.2	380.03	289.79	989.55	407.82	315.65
Gurgaon	876,969	1327.53	100.78	33.22	1309.21	115.01	37.31
Hyderabad	6,731,790	62.74	67.91	55.49	48.65	72.89	64.59
Kolkata	4,496,694	37.38	42.7	18.51	25.66	52.25	20.67
Mumbai	12,442,373	275.09	167.81	63.47	266.55	171.61	68.22

Table (3) Description of the areas under study

2016 | 2019	C1	C2	C3	C4	C5
C1	4	1	0	0	0
C2	1	69	7	0	0
C3	0	0	12	1	2
C4	0	0	0	5	0
C5	0	0	0	0	0
NULL	8	38	1	0	0

(a) Bangalore

2016 | 2019	C1	C2	C3	C4	C5
C1	8	0	0	0	0
C2	1	59	10	0	0
C3	0	0	31	0	1
C4	0	0	0	4	1
C5	0	0	0	3	6
NULL	0	1	0	0	0

(b) Chennai

2016 | 2019	C1	C2	C3	C4	C5
C1	97	26	11	0	0
C2	3	105	17	0	0
C3	5	1	92	5	6
C4	0	2	0	70	4
C5	0	0	3	6	88
NULL	36	13	1	0	0

(c) Delhi

2016 | 2019	C1	C2	C3	C4	C5
C1	16	4	0	0	0
C2	1	43	4	0	0
C3	0	0	13	0	1
C4	0	0	0	4	1
C5	0	0	0	1	11
NULL	9	9	0	0	0

(d) Gurgaon

2016 | 2019	C1	C2	C3	C4	C5
C1	1	0	0	0	0
C2	0	30	15	0	0
C3	0	0	21	2	0
C4	0	0	0	19	5
C5	0	0	0	1	9
NULL	0	6	2	0	0

(e) Hyderabad

2016 | 2019	C1	C2	C3	C4	C5
C1	4	1	0	0	0
C2	0	21	3	0	0
C3	0	1	7	2	0
C4	0	0	0	7	1
C5	0	0	0	0	2
NULL	2	8	0	0	0

(f) Kolkata

2016 | 2019	C1	C2	C3	C4	C5
C1	40	10	1	0	0
C2	0	55	2	0	0
C3	7	1	35	1	2
C4	0	0	0	4	0
C5	0	0.	3	0	20
NULL	5	1	0	0	0

(g) Mumbai

Table (4) Intra-city transition matrices for C1-C5 urban grids, between 2016 to 2019

References

[1] Bansal, C., Singla, A., Kumar, A. S., Ahlawat, H. O., Jain, M., Singh, P., Kumar, P., Saha, R., Taparia, S., Yadav, S., and Seth, A. Characterizing the evolution of indian cities using satellite imagery and open street maps. In *Proceedings of the 3rd ACM SIGCAS Conference on Computing and Sustainable Societies* (2020 forthcoming).