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Infiltration Well Efficacy in Ciliwung Basin Based on Rainfall-Runoff Volumetric Analysis

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Abstract

Run-off management is the main challenge of every big city. Land availability, project timeframe, and financing are several issues regarding run-off management implementation, including Indonesia's Capital City, Jakarta. One of the engineering tools that used to reduce the negative impacts of run-off in Jakarta is Infiltration Well. Several researches on this topic confirm the positive impact of building infiltration well on small catchment area. This study aims to understand the efficacy of infiltration well project on big basin area, the Ciliwung Basin. Ciliwung basin is divided into two sub-basin, Upstream Ciliwung and Downstream Ciliwung. The analysis is performed using volumetric abstraction of infiltration well volume and daily infiltration rate. 4 rainfall stations are used in this study, 2-gauge rainfall stations on each basin. Infiltration well capacity is tested with different return-period rainfall based on daily and storm-rainfall (3-days cumulative rainfall). The results show that by implementing 1 million infiltration wells at each sub-basin the abstraction volume is below 10% for 10-year return period rainfall and below 5% for 25-year return period rainfall.

Keywords: Rainfall-Runoff, Ciliwung Basin, Infiltration Well, Abstraction

INTRODUCTION

Run-off management is the main challenge of every big city, including Jakarta, Indonesia's Capital City. Land availability, project timeframe and financing are several issues regarding run-off management implementation project. One of the engineering tools that used to reduce the negative impacts of run-off in Jakarta is Infiltration Well. The term Infiltration Well in Indonesia can be traced back to Sunjoto on 1994 [1]. The basis of infiltration well formula he proposed was derived from previous study on 1988. The infiltation well formula is then used until now in the form of Indonesia National Code (Standar Nasional Indonesia) [2].

The concept of infiltration well was proposed to be implemented in small catchment with relatively small design rainfall. Even in small catchment such as residential house the abstraction is quite low or the required number and dimension of infiltration well is big if analysis is done using Infiltration Well National Code [3] [4]. Research done in Bogor Regency [5] ,using direct volumetric of infiltration well, conclude that infiltration well is effective to reduce 70% rainfall with magnitude of 97.36 mm/day, the number of infiltration wells needed are 115 with additional infiltration trenches of 76.

The real challenge is arise when infiltration well is implemented in big basin level. The big size of basin area, variety of land covers, and placement technical aspect should be assessed throuhgly. Another study of infiltration well eficacy in Upstream Ciliwiung Basin [6] show that by placing 13500-67500 infiltration wells peak discharge is reduce by 3-14%, the analysis was done by using HEC-HMS and sink formula different from National Code.

On bigger basin, the volume of run-off is rising along with the rise of basin area, assumed that the rainfall is spatially uniform. The temporal frame of rainfall also becoming significant role on basin level, rainfall that occurs more than a day will lessen the infiltration capacity. Puddle, and could lead to flood, will easily take place when rain is happening more than a day. To test rainfall-runoff analysis for such rainfall, the term storm-rainfall is used. Storm-rainfall is defined as 3-days cumulative rainfall.

Thus, this study is expected to understand the efficacy of huge numbers of infiltration well implementation in Upstream and Downstream Ciliwung Basin. The basin is selected as the term and implementation of infiltration well are mostly coming from area within the basin, such as Jakarta, Depok, and Bogor region.

METHOD

The methods used in this study, in order, are as follows:

- Regional Rainfall Analysis
- Outlier Test
- Gumbel Distribution & Design Rainfall
- Kolmogorov-Smirnov
- Horton Infiltration
- Infiltration Well Volume Capacity
- Runoff Volume

Detailed description of each point is shown below:

1. Ciliwung Basin

Ciliwung Basin is the the catchment area of Ciliwung River, measuring 374 km2 in area. Upstream is located around Mount Gede and Mount Pangrango, while downstream is located at North Jakarta Shore.

2. Rainfall Data

Upstream and downstream definition for Ciliwung basin is based Katulampa gate. Area located southern from Katulampa is defined as upstream and northern from it is defined as downstream.

Figure 1. Ciliwung Basin

Rainfall data used for the study are taken from:
•Upstream: Citeko and Bogor Rainfall Station year 2000-2020
•Downstream: Halim and Tanjung Priok Rainfall Station year 2000-2020.

3. Regional Rainfall Analysis

Arithmetic average is used as main regional rainfall analysis. Regional rainfall analysis is performed to determine the uniform rainfall height over the basin [7].

$$R_{reg} = \frac{R_a + R_b + \cdots + R_n}{N} \quad (1)$$

Where:
Rreg = Regional rainfall (mm)
Ra, Rb, ..., Rn = Rainfall at each gauge-station (mm)

4. Outlier Test

Outlier is the data that statistically very different data compared to the other normal empirical data. Outlier will make statistic prediction be overestimated and/or underestimated and will lead to wrong conclusion. The test used in this study is based on Tuckey's Fences, a nonparametric test that is simple to use. Outlier range based on this test is as follows:

$$[Q_1 - k(Q_3 - Q_1), Q_3 + k(Q_3 - Q_1)] \quad (2)$$

Where:
Q1 = Lower quartile
Q3 = Upper quartile
k = Outlier coefficient (1,5)

5. Gumbel Distribution and Design Rainfall

Gumbel distribution is used to generate rainfall data distribution based on Gumbel formula. The output of gumbel distribution is used as design rainfall. The formula is as follows [7]:

$$R_{Tr} = R_{ave} + S.K_{Tr} \quad (3)$$

Where:
RTr = Design rainfall (mm)
Rave = Average rainfall (mm)
S = Rainfall data standard deviation
KTr = Return period coefficient

6. K-S Test

Kolmogorov-Smirnov (KS) Test is a nonparametric fitness test to comparing two samples [8]. This test is quantifying the distance between sample empirical distribution function and the cumulative distribution function that is used. The hypothesis and maximum distance allowed formula of K-S test are as follows:

$$H_o: F = G \quad (4)$$

Minimum distance allowed

$$D_{min} = max_x[F_n(x) - G_n(x)] \quad (5)$$

Where:
F = Empirical distribution function
G = Cumulative distribution function
Dmin = Minimum distance allowed

7. Horton Infiltration

Infiltration rate calculation is based on Horton infiltration formula [9]. The formula is as follows:

$$f = f_c + ((f_o - f_c)e^{-ct} \quad (6)$$

Where:
f = Infiltration rate at t (time) (cm)
fc = Constant infiltration rate (cm/hour)
fo = Initial infiltration rate (cm/hour)
c = Soil decay constant
t = Time (hour)

8. Infiltration Well Volume

Infiltration well volume capacity is the total cumulative of infiltration well with cylinder shape (Diameter D, and Height H) and total infiltration in one day calculated only at bottom side.

9. Rainfall Volume

Rainfall volume is the product of daily rainfall rate times basin area without other abstraction (runoff coefficient). Storm rainfall volume is the total rainfall at D-1, D, and D+1, the aim for calculating storm rainfall is to understand infiltration efficacy during an event of rainfall more than one day, this event will lessen soil infiltration capacity. The infiltration rate for storm rainfall is assumed daily since the soil is highly saturated from previous rain day.

10. Efficacy Calculation

To calculate infiltration well efficacy direct volumetric abstraction is calculated as follows:

$$Eff. = \frac{Infiltration\ Well\ Volume}{Rainfall\ Volume} \quad (7)$$

Direct abstraction is more favorable calculation to understand infiltration well capacity in recent research and studies [10] [11] [12] [13] [14] [15]. The formula provides more rational infiltration well volume as the volume is calculated as follows:

$$Vol. Infiltration = \frac{\pi.D^2.H}{4} + \frac{\pi.D^2.f}{4} \quad (8)$$

Where:
D = Infiltration well diameter (m)
H = Infiltration well depth (m)
f = Initial infiltration rate (m/day)

RESULTS AND DISCUSSION

1. Regional Rainfall Analysis

   Regional rainfall analysis result for maximum daily and storm rainfall is shown in Table 1 to Table 4. By looking into the maximum daily rainfall, downstream Ciliwung basin had bigger rainfall events compared to upstream basin. But for storm rainfall event, both sub basin experienced relatively the same magnitude of rainfall.

2. Outlier Test

   Outlier test is performed for all datasets, upstream and downstream, maximum daily and storm rainfall. The resume of outlier test is stated below:
   - Downstream Ciliwung maximum daily rainfall, upper boundary is 182 mm/day and lower boundary is 64 mm/day, no outlier.
   - Downstream Ciliwung storm rainfall, upper boundary is 230 mm/day and lower boundary is 117 mm/day, no outlier.
   - Upstream Ciliwung maximum daily rainfall, upper boundary is 138 mm/day and lower boundary is 65 mm/hari, one outlier is removed.
   - Upstream Ciliwung storm rainfall, upper boundary is 233 mm/day and lower boundary is 74 mm/day, no outlier.

Table 1. Downstream Ciliwung Maximum Daily Rainfall

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Maximum Daily Rainfall
2000	65	59	29	36	31	14	26	16	28	43	7	41	65
2001	59	45	64	36	52	23	44	27	38	36	44	26	64
2002	147	123	89	22	6	23	1	0	0	38	33	81	147
2003	46	99	37	17	0	1	2	37	67	36	126	29	126
2004	57	102	76	16	19	25	10	5	13	74	50	121	121
2005	89	110	80	29	37	46	7	23	91	20	27	37	110
2006	35	90	55	32	27	34	44	0	0	35	33	67	90
2007	46	182	32	54	29	18	37	53	17	15	42	121	182
2008	44	112	56	62	47	20	0	20	18	12	51	57	112
2009	149	87	35	71	69	22	16	95	15	20	61	41	149
2010	86	88	40	22	85	28	24	34	67	67	50	36	88

2011	20	158	31	13	64	33	51	10	6	34	70	66	158
2012	53	91	60	39	36	36	13	0	25	39	41	58	91
2013	118	49	88	50	57	31	41	72	5	42	66	82	118
2014	135	77	95	37	87	28	36	72	54	6	58	58	135
2015	70	132	125	47	27	28	3	2	16	1	92	87	132
2016	61	58	39	112	44	60	43	45	73	54	80	38	112
2017	59	149	42	92	44	55	20	19	43	55	31	62	149
2018	49	101	65	69	41	16	1	46	15	63	50	34	101
2019	128	72	130	17	14	1	0	0	0	1	29	103	130
2020	146	156	47	58	22	32	56	74	6	58	59	44	156

Table 2. Upstream Ciliwung Maximum Daily Rainfall

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Maximum Daily Rainfall
2000	55	58	18	58	60	60	63	49	56	43	65	20	65
2001	71	88	63	41	55	41	78	50	84	52	58	46	88
2002	137	93	62	59	35	86	50	38	38	54	67	57	137
2003	29	87	54	80	74	75	25	42	63	63	47	56	87
2004	51	54	43	67	61	52	66	24	53	83	41	66	83
2005	138	87	108	55	56	53	35	46	50	63	80	22	138
2006	92	41	21	20	52	44	5	61	23	39	49	51	92
2007	102	83	41	91	28	30	36	54	60	49	79	62	102
2008	80	73	81	58	44	46	102	39	96	54	70	35	102
2009	93	60	50	48	83	78	54	16	29	53	46	40	93
2010	52	63	53	15	51	70	50	56	92	55	53	30	92
2011	58	37	22	37	64	41	88	57	17	53	80	41	88
2012	35	59	29	116	27	35	40	58	58	53	55	46	116
2013	87	83	101	60	77	37	56	34	19	45	46	77	101
2014	122	68	36	100	99	49	71	76	19	58	90	92	122
2015	28	64	63	45	35	32	1	95	28	32	103	55	103
2016	74	59	46	63	41	66	60	33	56	53	64	28	74
2017	29	54	55	51	48	76	40	47	63	60	46	32	76
2018	35	91	79	41	72	71	18	42	59	61	54	38	91
2019	45	71	39	101	79	34	22	30	79	87	54	90	101
2020	55	118	77	69	63	34	37	32	84	65	23	48	118

Table 3. Downstream Ciliwung Storm Rainfall

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Maximum Daily Rainfall
2000	131	123	40	58	49	54	14	26	16	14	35	11	131
2001	103	98	74	29	36	61	23	117	32	68	103	103	117
2002	256	215	79	86	23	8	23	1	0	0	46	39	256
2003	40	140	38	40	6	0	1	2	47	80	61	88	140
2004	89	198	82	133	24	21	25	10	5	26	89	76	198
2005	209	196	117	43	55	73	8	39	91	23	24	16	209

2006	59	163	87	34	27	34	44	0	0	38	67	92	163
2007	234	289	59	86	36	53	49	61	17	15	59	193	289
2008	173	163	60	62	58	56	0	24	29	17	69	37	173
2009	207	146	52	83	76	35	16	96	15	20	103	8	207
2010	137	148	46	33	97	53	28	54	84	77	57	46	148
2011	46	195	31	21	58	26	51	14	3	35	79	82	195
2012	126	124	67	38	51	65	13	0	25	47	77	73	126
2013	201	51	118	50	75	39	56	104	10	60	111	100	201
2014	290	156	68	42	34	45	45	110	59	6	102	89	290
2015	89	265	149	78	50	29	3	3	16	1	114	154	265
2016	77	126	85	118	62	89	81	79	77	80	88	26	126
2017	68	182	81	107	44	82	54	20	64	55	70	90	182
2018	88	82	74	168	45	25	3	66	15	66	87	26	168
2019	149	82	231	35	21	1	0	0	0	1	29	154	231
2020	160	175	56	62	39	32	56	74	6	58	72	109	175

Table 4. Upstream Ciliwung Storm Rainfall

Year/ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Maximum Daily Rainfall
2000	82	116	38	41	68	65	34	60	93	44	66	19	116
2001	60	78	35	66	68	85	125	20	62	44	57	14	125
2002	230	100	115	113	35	65	90	62	59	90	92	62	230
2003	32	95	55	52	139	82	0	93	59	104	60	59	139
2004	74	92	73	107	35	38	44	146	53	27	52	129	146
2005	154	101	120	36	107	135	109	54	101	89	119	38	154
2006	180	80	22	45	52	51	71	68	23	89	58	63	180
2007	148	233	94	122	56	45	112	94	70	74	129	102	233
2008	137	108	158	117	83	60	102	70	179	146	140	44	179
2009	128	82	32	60	53	47	95	20	21	58	46	44	128
2010	74	70	56	15	62	21	13	85	180	64	43	21	180
2011	25	34	23	60	60	54	104	31	34	65	54	29	104
2012	85	106	54	160	24	21	27	68	88	69	87	81	160
2013	193	34	30	51	57	31	77	68	19	67	51	112	193
2014	209	146	41	104	172	64	113	113	23	158	102	43	209
2015	43	94	126	57	41	44	95	95	32	18	95	119	126
2016	52	108	94	97	51	95	51	29	74	67	90	15	108
2017	31	106	41	48	46	47	40	31	78	58	46	40	106
2018	69	212	47	49	71	25	17	52	37	37	58	30	212
2019	53	38	14	122	38	34	24	56	92	98	58	109	122
2020	190	171	153	134	136	73	52	39	88	115	44	83	190

3. Design Rainfall

Gumbel distribution is acceptable with K-S test distance value of 0.14 with maximum allowed value of 0.3.

Table 5. Downstream Ciliwung Daily Design Rainfall

Return Period	$R_{Tr}(mm)$
2	116
5	149
10	171
25	198
50	219
100	239

Table 6. Upstream Ciliwung Daily Design Rainfall

Return Period	$R_{Tr}(mm)$
2	96
5	116
10	130
25	147
50	159
100	172

Table 7. Downstream Ciliwung Storm Design Rainfall

Return Period	$R_{Tr}(mm)$
2	182
5	238
10	275
25	322
50	357
100	392

Table 8. Upstream Ciliwung Storm Design Rainfall

Return Period	$R_{Tr}(mm)$
2	153
5	197
10	227
25	264
50	291
100	319

Daily design rainfall of Downstream Ciliwung is greater than Upstream Ciliwung, at value around 30 mm for each return period. At storm event design rainfall, Upstream Ciliwung magnitude increase significantly above 75% while Downstream Ciliwung increase rate on average at 61%. Despite smaller daily design rainfall, Upstream Ciliwung experiencing almost the same rainfall rate on the day before and day after as Downstream Ciliwung.

4. Infiltration Rate

The actual infiltration rate might vary between area and soil type across Ciliwung basin. Hence uniform infiltration rate value for Ciliwung Basin is based on previous research by Dwinanti Rika [9]. The research was able to get infiltration rate around Depok, this value is used as infiltration rate for all Ciliwung Basin.. The value taken from the research are fo = 18.122 cm/hour, fc = 2.306 cm/hour, and c = 1. Total infiltration for all Ciliwung basin is 57.095 cm/day, shown in Table 9.

5. Infiltration Well Volume

Infiltration well is commonly built using reinforced-concrete or masonry for wall face against soil pressure. Another reason is for simple constructability using those materials.

That is the reason the infiltration rate is only calculated at the bottom side of infiltration well. Indonesia National Code [2] also stated the maximum soil water table allowed for infiltration well construction is -2.00 m below top soil. This value is then taken as design height of all infiltration well. The diameter is assumed to be 1 m. Thus, the effective of one infiltration well volume capacity is 2.02 m3 (infiltration well volume plus infiltration rate volume). Total number of infiltrations well is assumed 1 million in each basin.

Table 9. Ciliwung Basin Infiltration Rate

Time (Hour-)	Infiltration Rate (cm/hour)	Infiltration (cm)
1	3.882	3.882
2	2.463	6.345
3	2.322	8.667
4	2.308	10.975
5	2.306	13.281
6	2.306	15.587
7	2.306	17.893

8	2.306	20.199
9	2.306	22.505
10	2.306	24.811
11	2.306	27.117
12	2.306	29.423
13	2.306	31.729
14	2.306	34.035
15	2.306	36.341
16	2.306	38.647
17	2.306	40.953
18	2.306	43.259
19	2.306	45.565
20	2.306	47.871
21	2.306	50.177
22	2.306	52.483
23	2.306	54.789
24	2.306	57.095

6. Infiltration Well Efficacy

Infiltration well efficacy for each events, Upstream-Downstream, Daily-Storm Rainfall, are shown below.

Table 10. Downstream Ciliwung Daily Rainfall Efficacy

Return Period Year	Rainfall Plan mm/day	Runoff Volume (mil.m^3)	Abstraction Volume (mil.m^3)	Abstraction Perscentage %
2	116	24.71	2.02	8.2%
5	149	31.69	2.02	6.4%
10	171	36.31	2.02	5.6%
25	198	42.14	2.02	4.8%
50	219	46.48	2.02	4.3%
100	239	50.77	2.02	4.0%

Table 11. Upstream Ciliwung Daily Rainfall Efficacy

Return Period Year	Rainfall Plan mm/day	Runoff Volume (mil.m^3)	Abstraction Volume (mil.m^3)	Abstraction Perscentage %
2	96	14.48	2.02	13.9%
5	116	17.56	2.02	11.5%
10	130	19.60	2.02	10.3%
25	147	22.18	2.02	9.1%
50	159	24.09	2.02	8.4%
100	172	25.99	2.02	7.8%

Table 12. Downstream Ciliwung Storm Rainfall Efficacy

Return Period Year	Rainfall Plan mm/day	Runoff Volume (mil.m^3)	Abstraction Volume (mil.m^3)	Abstraction Perscentage %
2	182	38.74	2.02	5.2%
5	238	50.67	2.02	4.0%
10	275	58.56	2.02	3.4%
25	322	68.54	2.02	2.9%
50	357	75.94	2.02	2.7%
100	392	83.29	2.02	2.4%

Table 13. Upstream Ciliwung Storm Rainfall Efficacy

Return Period Year	Rainfall Plan mm/day	Runoff Volume (mil.m^3)	Abstraction Volume (mil.m^3)	Abstraction Perscentage %
2	153	32.50	2.02	6.2%
5	197	41.95	2.02	4.8%
10	227	48.20	2.02	4.2%
25	264	56.11	2.02	3.6%
50	291	61.97	2.02	3.3%
100	319	67.79	2.02	3.0%

The efficacy of 1 million infiltration well at each sub basin is low, below 10% on average for each return period of both event (daily and stormrainfall) except for 2-years return period of daily rainfall. To achieve this efficacy the infiltration well is assumed empty without filtration materials and permeable area only located at the bottom. The infiltration well effective volume to store rainwater will be lower if filtration material is provided. To increase the efficacy the option is either increase the infiltration well dimension and/or to consider infiltration at the curved surface that often only have limited amount of hole intended to provide infiltration to the side.

Effective infiltration rate around the curved face also has to be carefully calculated because if infiltration is allowed around the infiltration well, by selecting permeable material, the effective infiltration surface should be below the infiltration depth value that used as design. For example, the effective infiltration height is only 1.43 m if infiltration well of 2 m depth is selected and 57 cm/day infiltration is taken. One other thing to be considered is hydraulic conductivity. Infiltration or vertical hydraulic conductivity is more common term used in Civil Engineering, while the horizontal hydraulic conductivity is rarely used. The flow rate along the curved face should be calculated using horizontal hydraulic conductivity rather than using the infiltration rate value. Horizontal hydraulic conductivity is varying greatly along horizontal spatial boundary [16]. To find better efficacy calculation more complex analysis is needed.

CONCLUSIONS

Data collected and analyze shows that downstream Ciliwung basin had bigger rainfall events compared to upstream basin. But for storm rainfall event, both sub basin experienced relatively the same magnitude of rainfall. Despite smaller daily design rainfall, Upstream Ciliwung experiencing almost the same rainfall rate on the day before and day after as Downstream Ciliwung. Infiltration well efficacy on each rainfall event in Ciliwung basin based on 1 million units (D = 1 m & H = 2 m) are relatively low, below 10% of abstraction of total rainfall volume. Except for upstream Ciliwung rainfall event of 10-year return period. The efficacy is decreasing for higher return period rainfall. At 25-year return period the efficacy is below 5% except for upstream Ciliwung rainfall event. Actual effective infiltration well volume might be less at downstream area, especially North of Jakarta area where sea water intrusion is high and higher groundwater level is expected. In order to increase infiltration well efficacy bigger dimension is favorable than calculating hydraulic conductivity along its horizontal face.

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