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Technical Notes:
Computational Model for Housing Drainage System
Case Study: Kharismatama Permai Housing in Padang

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Abstract

This study is about the development of a computational model, which is capable of simulating flows flowing through roadside gutters in a housing drainage system with a very mild-slope land in a steady state condition. The governing equation of the model is the world-widely used uniform flow formulation by Manning. The equation is solved using the Newton-Raphson method. The resulting model is then applied to simulation of gutter flows flowing across a drainage system of Kharismatama Permai housing in Padang, which is frequently overflowed by the rainfall excess. The rate of rainfall intensity was measured manually at the same time the flood occurred at the considered housing complex. Types of gutter materials were observed to determine the coefficients of gutter roughness, and types of land covers also were observed to determine the run-off coefficients. By adjusting the gutter slopes and varying the flow directions, the drainage system can flow the rainfall excess without overflowing.

Keywords: *Rainfall, gutter, flow, slope, flow direction, model.*

Abstrak

Penelitian ini adalah tentang pengembangan sebuah model komputasi yang dapat mensimulasikan aliran yang melewati saluran samping jalan dalam sistem drainase komplek perumahan yang mempunyai lahan yang sangat landai dalam kondisi tidak bergantung waktu. Persamaan pengaturnya adalah persamaan aliran seragam Manning yang telah digunakan secara luas di seluruh dunia. Persamaan tersebut diselesaikan dengan menggunakan metode Newton-Raphson. Model ini diaplikasikan untuk mensimulasikan aliran saluran samping jalan dalam sistem drainase Perumahan Kharismatama Permai di Padang, yang sering banjir akibat sisa hujan. Intensitas curahan hujan diukur secara manual pada waktu yang sama banjir terjadi pada komplek perumahan tersebut. Jenis bahan tubuh saluran diamati untuk menentukan koefisien kekasaran saluran, dan jenis penutup lahan juga diamati untuk menentukan koefisien limpasan. Dengan mengatur kemiringan saluran dan mengubah arah alirannya, sistem drainase tersebut dapat mengalirkan sisa hujan tanpa banjir.

Kata-kata Kunci: *Curahan hujan, saluran samping jalan, debit, kemiringan, arah aliran, model.*

1. Introduction

When a rainfall with a high intensity falls on a very mild-slope housing land, the rainfall excess then slowly flows to roadside gutters across the land. The water then slowly flows following the gutter slopes. Consequently, the water depth increases significantly. A lower gutter gravitationally receives an additional flow from an upper gutter in case of both gutters are linked. As a result, the lower gutters automatically convey the greater flow than the upper gutters do. A lower gutter may be linked by more than one of upper gutters. This may cause the water overflowing in the lower gutters.

The situation mentioned above frequently happened in some residential areas with a very mild-slope land. To solve this problem, the rate of the conveyance of gutter sections should be increased. The width of the gutters cannot be widened, since it can narrow the road width. Instead, the slope of the gutters (and also the flow directions) can be adjusted to get rid of flooding.

As a result, the present study devotes to solving overwhelming rainfall excess in residential areas with a very mild-slope land by considering the adjustment of the gutter slopes and the flow directions to increase the rate of the conveyance of gutter sections. Consequently, the primary objective of the present study is to develop a computational model, which is capable of predicting the water depth in every segment of the gutter in a residential area with a very mild-slope land. To do this, some secondary objectives are needed, *i.e.*: (1) surveying to find a residential area with a very mild-slope land, which is frequently overwhelmed by the rainfall excess; (2) measuring the rainfall intensity in the considered residential area; (3) measure the geometric of gutters in the considered residential area; (4) observing the types of gutter materials in the considered residential area; and (5) observing the land covers in the considered residential area.

2. Governing Equation

As referred by Wikipedia (2010), an Irish engineer, Robert Manning in 1890, presented a formula, which was modified to its present well-known form, *i.e.*

$$v = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (1)$$

where v is the average horizontal velocity of flow in m/s; n is the roughness coefficient of Manning; R is the hydraulic radius in m; and S is the gutter slope in m/m. The hydraulic radius R is obtained from the water area A divided by the wetted perimeter P. The values of the roughness coefficients n were tabulated by Chow (1973), and the values of S and the geometric of the gutters are obtained by measurement.

The velocity can be expressed as

$$v = \frac{Q}{A} \qquad (2)$$

where Q is the flow or discharge in m^3/s. As a result, the **Equation (1)** leads to

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (3)$$

Due to the **Equation (3)** is a steady state one, the peak flow should be used in the case of a small watershed. This was confirmed by Bedient and Huber (1992) that urban development of a natural basin or watershed will usually result in increased peak outflows and shorter responses times as development proceeds. Small watershed designs usually involve the use of either the rational method or a unit hydrograph procedure to predict peak flows at various places for a given design rainfall and duration. The rational method is then used since it is the simplest rainfall-runoff formula. More detailed Bedient and Huber (1992) explained that the concept behind the rational method lies in the assumption that a steady, uniform rainfall rate will produce maximum run-off when all parts of a watershed are contributing to outflow, a condition that is met after the time of concentration tc has elapsed. The rational method can be expressed as

$$Q = C\, i\, A_{ws} \qquad (4)$$

in which Q is the peak flow; C is the run-off coefficient; i is the rainfall intensity in m/s; and A_{ws} is the watershed area in square meter. The values of the coefficients C with respect to return periods of 2, 5, 10, 25, 50, 100 and 500 years can be found in Chow *et al.* (1988). The flow Q conveyed by a gutter is assumed to be a constant along the considered gutter.

The water area A and the hydraulic radius R are function of the water depth y, so that the solution of the **Equation (3)** is the water depth.

3. Numerical Solution Algorithm

Since R = A / P, **Equation (3)** can be expressed as

$$Q = \frac{1}{n} \frac{A^{\frac{5}{3}}}{P^{\frac{2}{3}}} S^{\frac{1}{2}} \qquad (5)$$

or

$$\frac{Qn}{S^{\frac{1}{2}}} = \frac{A^{\frac{5}{3}}}{P^{\frac{2}{3}}} \qquad (6)$$

If **Equation (6)** powered by 3/2 leads to

$$\left(\frac{Qn}{S^{0.5}}\right)^{1.5} P - A^{2.5} = 0 \qquad (7)$$

Every single gutter is assumed to be a prismatic channel. For a gutter with a rectangular section as shown in **Figure 1**, the water area A and the wetted perimeter P can be stated respectively as

$$A = by \qquad (8)$$

$$P = b + 2y \qquad (9)$$

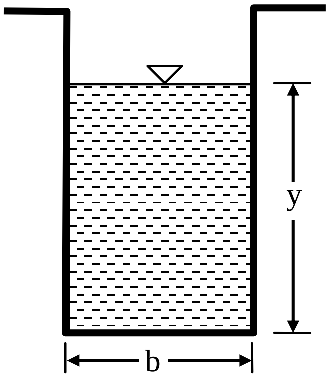

Figure 1. Rectangular section

Due to P and A are a function of y, **Equation (7)** can be expresses as

$$f(y) = aP - A^{2.5} = 0 \tag{10}$$

where:

$$a = \left(\frac{Qn}{S^{0.5}}\right)^{1.5} \tag{11}$$

Substitution of **Equations (8)** and **(9)** into **Equation (10)** gives

$$f(y) = a(b + 2y) - (by)^{2.5} \tag{12}$$

The differential form of **Equation (12)** with respect to the water depth y is

$$\frac{df(y)}{dy} = f'(y) = 2a - 2.5bA^{1.5} \tag{13}$$

Now, the water depth y can be solved using the Newton-Raphson method (Kreyszig, 1988)

$$y_{i+1} = y_i - \frac{f(y_i)}{f'(y_i)} \tag{14}$$

where the initial value y_1 is an arbitrary value and y_2 is y value in the first iteration. The iteration should be stopped if

$$\left|y_{i+1} - y_i\right| \le 0.001 \tag{15}$$

4. Field Measurement and Observation

A field measurement is conducted by Dewi (2008) to collect all gutter-related parameters *i.e.* the gutter width b; the gutter depth d; the gutter lengths; and the gutter slope S. Such measurement was applied to all roadside gutters in the housing of *Kharismatama Permai* in Padang (see **Figure 2**). The measurement of the parameters b, d and the length of the gutters was done by using a meter tape or a rod (a staff). However, to collect the data of the gutter slopes S, the elevation of the slope bases was measured by using a water-pass. The watershed area A_{ws} was also measured to predict the flow Q.

Figure 2. *Kharismatama permai* housing (Google Earth image, 2010)

During the measurement, the materials of the gutters are also inspected to determine the roughness coefficients of Manning. Overall, the gutters were made from unfinished concrete. This gives the roughness coefficient of Manning n = 0.20 (Chow, 1973).

To predict the rate of rainfall intensity in a given area especially for designing a drainage system, the use of rainfall data with short periods is strongly recommended. However, these data are unavailable in Padang, but daily rainfall data. As a result, we measured it manually by using a cylinder and a stopwatch. The measurement was done at the same time when flood occurred in the housing of *Kharismatama Permai*. The measurement gave 136 mm/hour for the rate of rainfall intensity.

As a comparison, the maximum daily rainfall data recorded by Tabing weather station in Padang, i.e. the nearest station to the considered housing, from year 1986 to 2008 gives an average of 287.6 mm a year with a standard deviation of 195.6 mm (in the logs of data gives an average of 2.3920 a year with a standard deviation of 0.2268 and a skewness of 1.4551). Since the data are extremes (maxima), an extreme probability distribution model, say the Log-Pearson type 3 distribution, can be used to predict the quantity of rainfall for certain return periods T. If the Mononobe formula is used to predict the rate of rainfall intensity, an IDF (intensity, duration, frequency) curve can be made as shown in **Figure 3**. The intensity rate of the measurement result is comparable to that of the prediction results for the return period of 50 years with a duration of 4 hours. In the reality, the rate of about 136 mm/hour (as one measured manually) occurred frequently especially in rainy season in every year from year 1986 to 2008. This was confirmed by some residents of the housing. This phenomenon indicates that short period data should be used in predicting the rate of rainfall intensity.

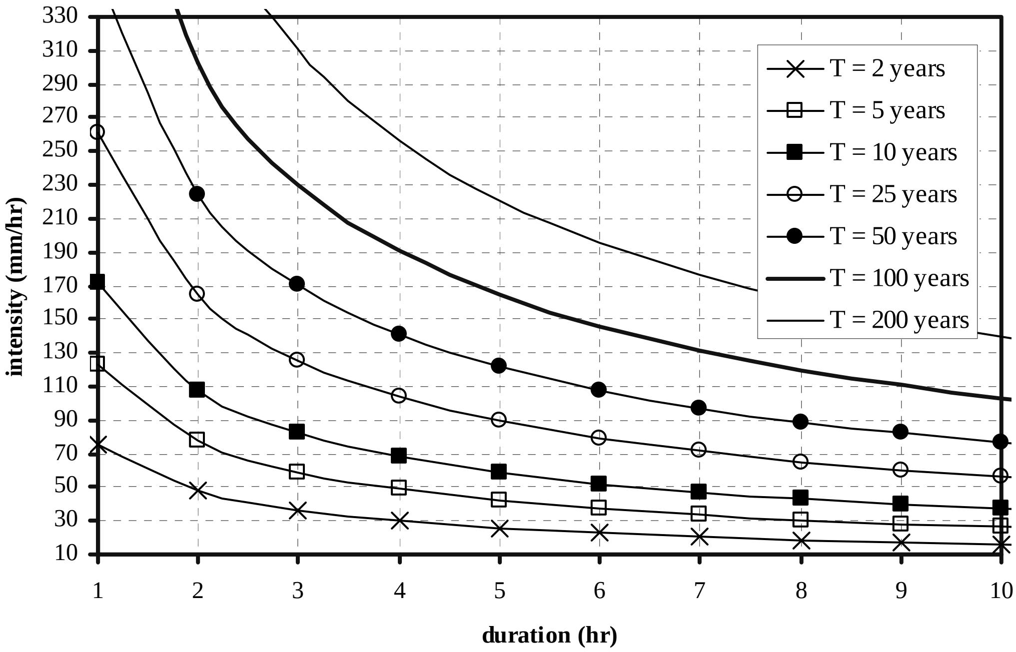

Figure 3. IDF curve based on the maximum daily rainfall

The land covers in the housing of *Kharismatama Permai* in Padang were also observed to determine appropriate values for run-off coefficients C. Generally, the surface layers of the roads in the considered residential area were asphalts. If the roads are presumed to cover the area about 20%, and about 80% of the rest (i.e. 64%) is covered by concrete and roof, and the rest is about 16% for the grass area such as lawns and parks. Based on Chow *et al*. (1988) for a return period of 50 years, the run-off coefficients are 0.9 for the roads, 0.92 for concrete and roof, and 0.44 for grass. By considering an area-weighting factor gives an average value for C = 0.84.

All parameters obtained are inserted to the governing equation to predict the water depths in every gutter segment. Based on the measurement, the existing flow directions can be identified as shown in **Figure 4**

5. Numerical Set-up

The present numerical model is applied to simulation of the existing flow directions flowing in the road side gutters in the housing of *Kharismatama Permai* as shown in **Figure 4**. The numerical results are shown in **Table 1**.

Table 1 shows that 13 gutters are overflowed, *i.e.* gutters with numbers 2, 5, 7, 10, 14, 15, 17, 24, 26, 28, 29, 30 and 31. Gutters with numbers 2, 17, 24, 26 and 29 are blocked at the downstream. Meanwhile, gutters with numbers 14, 15, 28, 30 and 31 cannot convey flow due to their slopes being flat. The present model is capable of identifying the overflowed gutters as they happen in the considered real drainage system.

To solve these problems, some flow directions are changed; base slopes are adjusted and culverts are added to connect one gutter to another as shown in **Figure 5**. The numerical results based on the reviewed conditions are shown in **Table 2**.

Tabel 2 shows that all gutters are capable of conveying flows properly without overflowing. This is done by:

1. adjusting all the slopes of the gutters except the gutters with numbers 3, 6, 9, 12, 16, 17, 18, 19, 21 and 22;
2. changing flow directions of the guters with numbers 2, 4, 5, 14, 15, 24, 25, 26, 27, 28, 29, 30 and 21;
3. adding a culvert at the downstream of the gutters with numbers 7, 24, 25, 26, 27, 28, 30 and 31.

6. Conclusions

1. A numerical model, which is applicable of simulation of flows flowing through road side gutters across a housing drainage system with a very mild-slope land in a steady state condition, is developed.
2. The governing equation is the world-widely used uniform flow formulation of Manning. The governing equation is solved using the Newton-Raphson method.
3. Comparison between the present numerical model results and the field data shows that the present model is capable of identifying the overflowed gutters as they happen in the considered real drainage system.

7. Recommendations

The present model still needs to be verified by comparing the results of the present model based on the reviewed condition to the field data. Of course, this is very expensive, because the considered real drainage system has to be re-dug following the recommendation of the present model results. Alternatively, it can be done by making a physical model in a laboratory.

8. Acknowledgements

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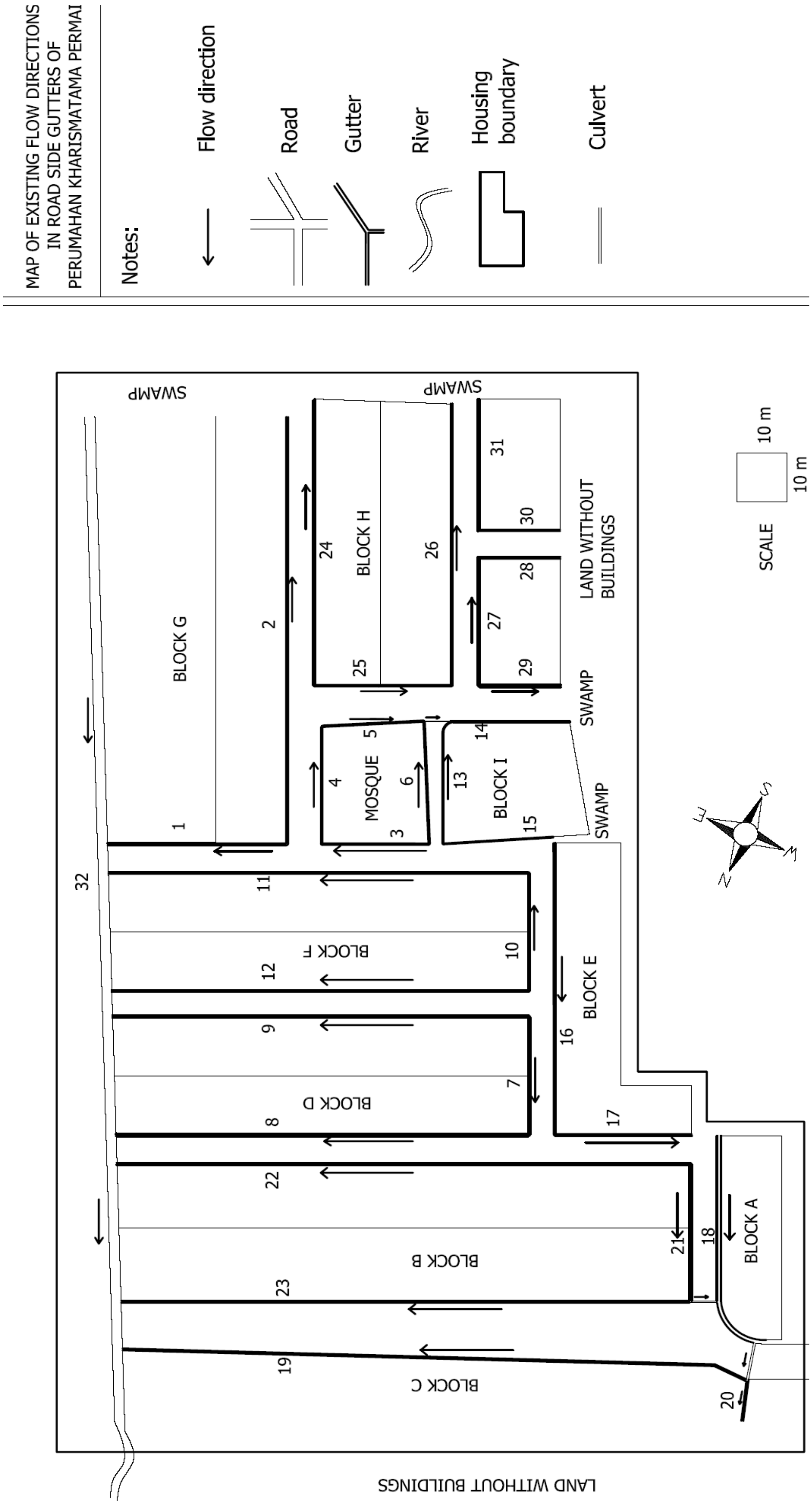

Figure 5. Varied flow directions in the road side gutters in Kharismatama Permai housing

Tabel 1. Numerical results based on the existing condition

Flat

Intensity i is 136 mm/hr and run-off coefficient C is 0,84										Number of overflowed segments is 13					
Number	**Geometry (cm)**		**n**	**Base Elevation (cm)**		**Length**	**Slope S**	**Water-shed Area**	**Flow Qj**	**Additional Flow Qa**		**Total Flow Qt**	**Water Depth y**	**Notes**	
j	**b**	**d**		**Up**	**Down**	**(m)**		**(m^2)**	**(m^3/s)**	**(m^3/s)**		**(m^3/s)**	**(cm)**		
1	40	40	0,020	1.989	1.938	32	0,0159	1.496	0,0475			0,0475	11		
2	40	38	0,020	1.989	1.954	88	0,0039	875	0,0278			0,0278	**40**	Flood	Blocked
3	30	20	0,020	2.022	2.004	21	0,0086	310	0,0098			0,0098	6		
4	30	25	0,020	2.004	1.969	24	0,0146	300	0,0095	Q_3=	0,0098	0,0193	8		
5	30	30	0,020	1.969	1.968	20	0,0008	310	0,0098	Q_4=	0,0193	0,0292	**32**	Flood	
6	30	20	0,020	2.022	1.668	26	0,1363	306	0,0097			0,0097	2		
7	40	20	0,020	2.005	2.001	80	0,0004	988	0,0314			0,0314	**30**	Flood	
8	40	30	0,020	2.001	1.975	80	0,0032	850	0,0270	Q_7=	0,0314	0,0583	23		
9	40	25	0,020	2.005	1.957	24	0,0198	975	0,0309			0,0309	9		
10	30	20	0,020	2.004	2.000	24	0,0017	875	0,0278			0,0278	**22**	Flood	
11	35	40	0,020	2.000	1.981	80	0,0024	987	0,0313	Q_{10}=	0,0278	0,0591	29		
12	30	35	0,020	2.004	1.958	80	0,0058	1.010	0,0321			0,0321	15		
13	20	20	0,020	2.002	1.969	25	0,0132	344	0,0109			0,0109	8		
14	20	25	0,020	1.969	1.969	25	**0,0000**	338	0,0107	Q_{13}+ Q_6+ Q_5=	0,0498	0,0605	**40**	Flood	Flat
15	20	16	0,020	2.002	2.002	29	**0,0000**	443	0,0140			0,0140	**40**	Flood	Flat
16	35	35	0,020	1.995	1.991	60	0,0008	775	0,0246			0,0246	23		
17	35	25	0,020	1.991	1.970	27	0,0076	344	0,0109	Q_{16}=	0,0246	0,0355	**40**	Flood	Blocked
18	80	65	0,020	1.970	1.934	42	0,0086	651	0,0207	Q_{21}=	0,0529	0,0735	10		
19	40	50	0,020	1.982	1.929	124	0,0043	857	0,0272			0,0272	12		
20	40	60	0,020	1.931	1.929	15	0,0013	954	0,0303	Q_{18}=	0,0735	0,1038	52		
21	40	35	0,020	1.980	1.966	28	0,0052	1.666	0,0529			0,0529	18		
22	40	40	0,020	1.980	1.964	112	0,0014	1.764	0,0560			0,0560	30		
23	40	45	0,020	1.976	1.966	112	0,0009	1.316	0,0418			0,0418	28		
24	30	35	0,020	1.980	1.955	59	0,0042	915	0,0290			0,0290	**40**	Flood	Blocked
25	30	20	0,020	1.989	1.979	27	0,0039	735	0,0233			0,0233	14		
26	30	25	0,020	1.979	1.947	58	0,0055	957	0,0304			0,0304	**40**	Flood	Blocked
27	40	20	0,020	1.970	1.969	26	0,0005	273	0,0087			0,0087	11		
28	40	23	0,020	1.970	1.970	16	**0,0000**	256	0,0081			0,0081	**40**	Flood	Flat
29	40	35	0,020	1.970	1.948	16	0,0138	264	0,0084			0,0084	**40**	Flood	Blocked
30	30	27	0,020	1.980	1.980	16	**0,0000**	336	0,0107			0,0107	**40**	Flood	Flat
31	30	27	0,020	1.980	1.980	27	**0,0000**	284	0,0090			0,0090	**40**	Flood	Flat
32	200	90	0,025	1.925	1.919	204	0,0003	3.392	0,1076	Q_{23}+ Q_{22}+ Q_{19}+ Q_{12}+ Q_{11}+ Q_9+ Q_8+ Q_1=	0,3528	0,4605	62,65		

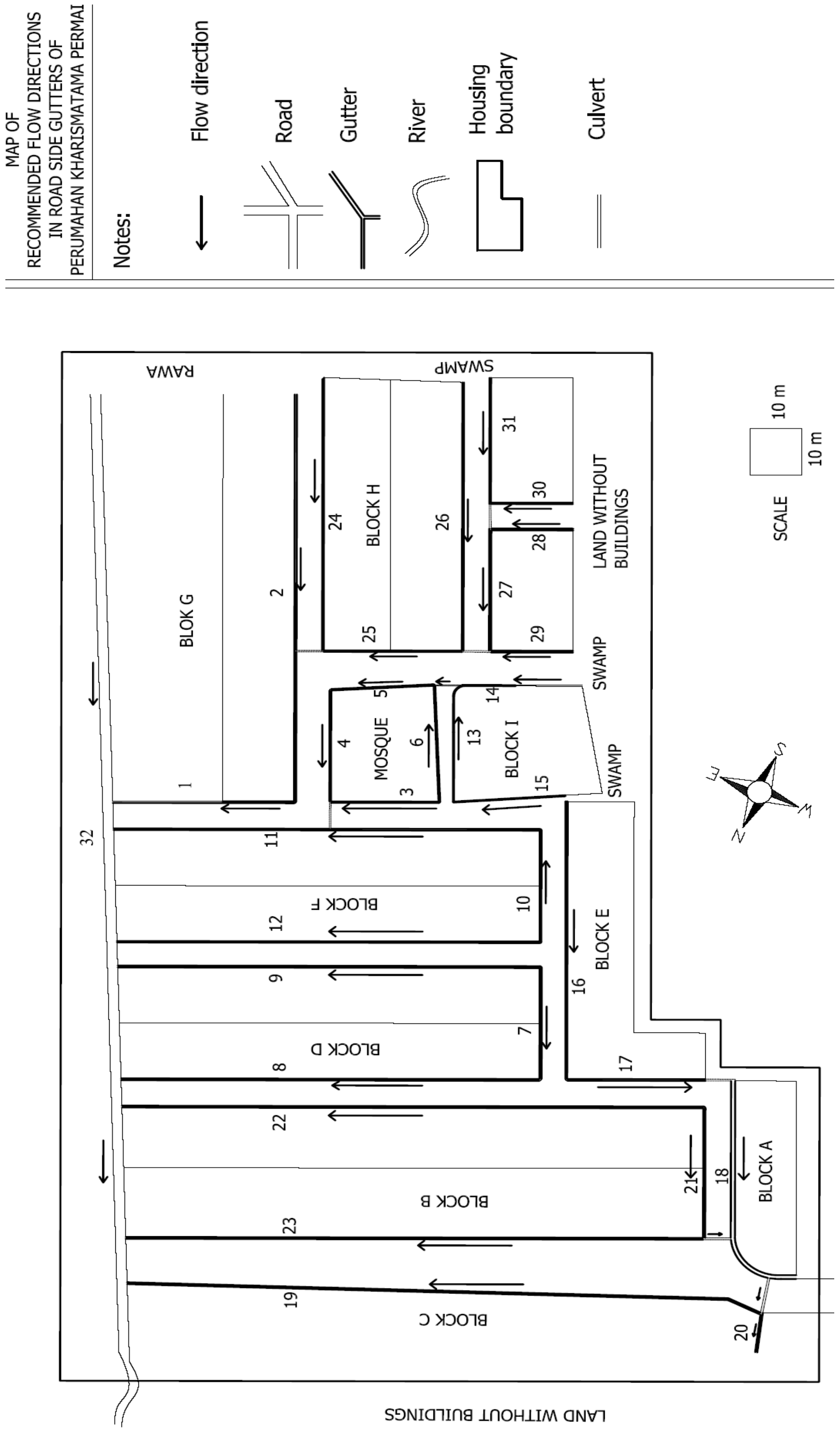

Figure 4. Existing flow directions in the road side gutters in Kharismatama Permai housing.

Table 2. Numerical results based on the reviewed condition

Number	Geometry (cm)		n	Base Elevation (cm)		Length	Slope S	Water-shed Area	Flow Qj	Additional Flow Qa	Total Flow Qt	Water Depth y	Notes	Changes
Intensity i is 136 mm/hr and run-off coefficient C is 0,84										**No. of overflowed segments is 0**				
j	**b**	**d**		**Up**	**Down**	**(m)**		**(m^2)**	**(m^3/s)**	**(m^3/s)**	**(m^3/s)**	**(cm)**		
1	40	**90**	0,020	**1935**	**1925**	32	0,0031	1.496	0,0475	$Q_2=$ 0,1550	0,2025	63		(1)
2	40	**90**	0,020	**1935**	1.954	88	0,0022	875	0,0278	$Q_{25}+Q_{24}=$ 0,1273	0,1550	59		(1)(2)
3	30	20	0,020	2.022	2.004	21	0,0086	310	0,0098		0,0098	6		
4	30	**70**	0,020	**1955**	**1950**	24	0,0021	300	0,0095	$Q_3=$ 0,0098	0,0193	16		(1)(2)
5	30	**48**	0,020	**1955**	**1950**	20	0,0025	310	0,0098	$Q_{14}+Q_{13}+Q_6=$ 0,0454	0,0552	33		(1)(2)
6	30	20	0,020	2.022	1.668	26	0,1363	306	0,0097		0,0097	2		
7	40	**30**	0,020	2.005	**1990**	80	0,0018	988	0,0314		0,0314	18		(1)
8	40	**40**	0,020	**1990**	1.975	80	0,0018	850	0,0270	$Q_7=$ 0,0314	0,0583	28		(1)
9	40	25	0,020	2.005	1.957	24	0,0198	975	0,0309		0,0309	8		
10	30	20	0,020	2.004	**1990**	24	0,0058	875	0,0278		0,0278	14		(1)
11	35	**70**	0,020	**1990**	**1930**	80	0,0075	987	0,0313	$Q_{10}+Q_4+Q_3=$ 0,0569	0,0883	26		(1)
12	30	35	0,020	2.004	1.958	80	0,0058	1.010	0,0321		0,0321	15		
13	20	**30**	0,020	**1990**	1.969	25	0,0086	344	0,0109	$Q_{15}=$ 0,0140	0,0250	17		(1)
14	**30**	**39**	0,020	1.969	**1955**	25	0,0056	338	0,0107		0,0107	7		(1)(2)
15	20	**25**	0,020	2.002	**1990**	29	0,0041	443	0,0140		0,0140	14		(1)(2)
16	35	35	0,020	1.995	1.991	60	0,0008	775	0,0246		0,0246	24		
17	35	25	0,020	1.991	1.970	27	0,0076	344	0,0109	$Q_{16}=$ 0,0246	0,0355	13		(3)
18	80	65	0,020	1.970	1.934	42	0,0086	651	0,0207	$Q_{21}+Q_{17}=$ 0,0627	0,0834	11		
19	40	50	0,020	1.982	1.929	124	0,0043	857	0,0272		0,0272	12		
20	40	**61**	0,020	1.931	**1928**	15	0,0019	954	0,0303	$Q_{18}=$ 0,0834	0,1136	47		(1)
21	40	35	0,020	1.980	1.966	28	0,0052	1.666	0,0529		0,0529	18		
22	40	40	0,020	1.980	1.964	112	0,0014	1.764	0,0560		0,0560	30		
23	40	**60**	0,020	**1966**	**1955**	112	0,0009	1.316	0,0418		0,0418	28		(1)
24	30	**60**	0,020	**1950**	1.955	59	0,0008	915	0,0290		0,0290	32		(1)(2)(3)
25	30	**75**	0,020	**1940**	**1930**	27	0,0037	735	0,0233	$Q_{29}+Q_{27}+Q_{26}=$ 0,0749	0,0983	46		(1)(2)(3)
26	30	**65**	0,020	**1940**	1.947	58	0,0011	957	0,0304		0,0304	28		(1)(2)(3)
27	40	**40**	0,020	**1948**	1.969	26	0,0080	273	0,0087	$Q_{31}+Q_{30}+Q_{28}=$ 0,0278	0,0364	12		(1)(2)(3)
28	40	**30**	0,020	1.970	**1965**	16	0,0031	256	0,0081		0,0081	6		(1)(2)
29	40	**65**	0,020	**1940**	1.948	16	0,0048	264	0,0084		0,0084	5		(1)(2)(3)
30	30	**30**	0,020	1.980	**1975**	16	0,0031	336	0,0107		0,0107	9		(1)(2)(3)
31	30	**30**	0,020	1.980	**1975**	27	0,0019	284	0,0090		0,0090	9		(1)(2)(3)
32	200	95,000	0,025	1.925	1915	204	0,0005	3.392	0,1076	$Q_{23}+Q_{22}+Q_{19}+Q_{12}+Q_{11}+Q_9+Q_8+Q_1=$ 0,5370	0,6447	66,37		(1)