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STREET STORM WATER CONVEYANCE CAPACITY

by

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Abstract The street hydraulic capacity to convey storm water is dictated by the street gutter geometry and hydraulic characteristics. With the consideration of traffic safety, the street hydraulic conveyance capacity is also subject to a reduction defined by the water velocity and flow depth in the street gutter. In this study, the street hydraulic equation is re-arranged to demonstrate that the water velocity and depth product in a gutter flow can serve as a safety criterion for determining the allowable street hydraulic conveyance capacity. Both the velocity and water depth product and discharge reduction methods were examined and revised to establish the consistency in predictions. The revised design procedures developed in this study replace the current iterative process with a direct estimation of the allowable street hydraulic conveyance capacity when a safety criterion is specified.

Key Words: street, hydraulic, gutter, water spread, storm water, runoff

INTRODUCTION

The primary function of a street is to facilitate traffic movement. However, during a storm event, streets must also collect and convey the concentrated stormwater runoff. If a street drainage system is not designed properly, the roadway system can be degraded to an unacceptable level of service during storm events. In practice, the street hydraulic conveyance capacity (SHCC) is firstly determined from the gutter geometry and street hydraulic characteristics, and then subject to safety considerations. If the street is so steep that the gutter flow will have high velocities, the SHCC must be reduced to its allowable street hydraulic conveyance capacity (ASHCC). The U.S. Department of Transportation published the Hydraulic Engineering Circular No. 12 (HEC-12) (1984) and Design of Urban Highway Drainage (1979). Both summarize the design procedures for determining the street hydraulic conveyance capacity based on the gutter geometry and other hydraulic factors. Although HEC-12 is considered as the technical guideline for street drainage designs, it falls short regarding the discharge reduction due to safety concerns (Guo, 1997). Many traffic accidents caused by dynamic hydroplaning occur on flooded pavements. The empirical equation for dynamic hydroplaning speeds was formulated by Agrawal et al (1977) using the condition that the brake force coefficient is reduced to zero to analyze the initiation of hydroplaning. Gallway et al. (1979) analyzed the vehicle speed at incipient hydroplaning by the parameter of spindown which is the change in rotational velocity of a wheel due to the loss of contact with the pavement surface during hydroplaning. Huebner, et al. (1986) presented an empirical equation between vehicle speed at incipient hydroplaning and water film thickness. The equation exhibits a hyperbolic relationship between vehicle velocity and water depth.

Water flowing on a street imposes a momentum impulse on vehicles and pedestrians. With a concept similar to the hydroplaning analysis, the hyperbolic relationship between water velocity (V) and depth (D) in a gutter flow has been adopted as a control of runoff discharge for street drainage designs. Both the VD product and discharge reduction methods have been developed from field experience. For instance, since 1968, the Storm Water Drainage Design Criteria Manual recommended by the City and County of Denver in the State of Colorado has adopted a set of discharge reduction factors for determining the SHCC. Since 1991, the Hydrologic Criteria and Drainage Design Manual published by Clark County for the 800-square mile Las Vegas area in the State of Nevada has suggested that the VD product of a street gutter flow be less than six for a minor event and eight for a major event when estimating the ASHCC.

The approach of discharge reduction is an explicit method using a set of empirical factors derived from field experience. On the other hand, the approach of VD products provides an implicit procedure that involves an iterative design process to convert the permissible VD product to a discharge reduction. Regardless of the inconsistency in predictions and inadequate understanding in theory, both methods have been adopted as empirical guidance for street drainage designs because of the increasing concerns about the safety of storm water flowing on streets.

Street curbs and gutters are designed to intercept storm water safely until the water spread becomes too wide and the flow velocity becomes too high. In this study, the street hydraulic equation is re-arranged for the condition of a wide water spread on a steep street. This derivation reveals that both the momentum impulse and the capacity per unit width in a gutter flow can be directly related to its VD product. Therefore, the VD product can serve as a criterion to consistently determine the ASHCC on a steep and wide street. Derivations in this study also mathematically relate discharge reduction factors to VD products and further lead to the developments of discharge reduction factors as a function of street slope and water spread width. With these modifications, a specified permissible VD product can be converted to its equivalent discharge reduction factor for a direct estimation of ASHCC without iterations.

STREET HYDRAULICS

Figure 1 illustrates a composite street gutter cross section. Storm water flowing through such a gutter section can be described by the revised Manning's equation as (Izzard 1946):

$$Q = \tfrac{K}{n} S_x{}^{1.67} T^{2.67} \sqrt{S_o} \qquad (1)$$

in which Q = street hydraulic conveyance capacity (SHCC), K=0.56 for the English system or 0.376 for the SI system, n = Manning's roughness of street surface, S_x = street transverse slope, S_o= street longitudinal slope, and T= water spread width on the street. In general, a value of 0.016 is recommended for Manning's roughness and 1% or 2% for street transverse slope.

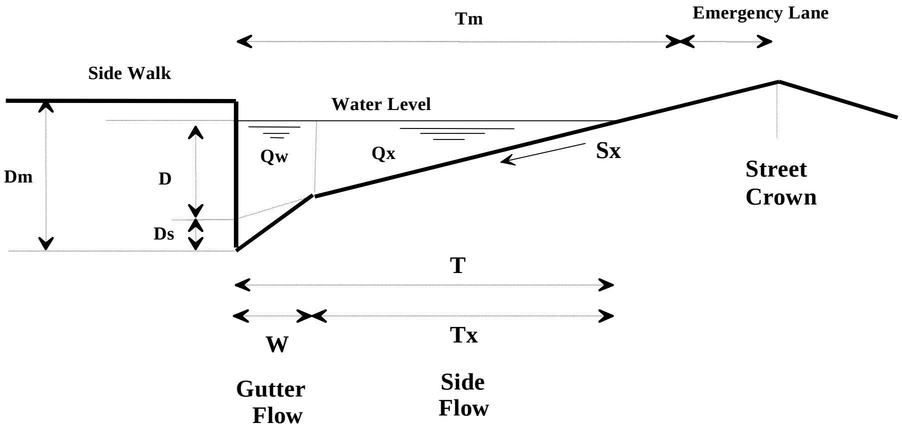

Figure 1 Hydraulic Parameters for Street Hydraulic Conveyance Capacity

As shown in Figure 1, the storm water collected by a street gutter is divided into a gutter flow which is the amount of flow carried within the gutter width, and a side flow which is the amount of flow carried by traffic lanes. Assuming that the friction on an internal water surface is negligible, Eq. 1 can be separately applied to both the gutter flow and the side flow. The total discharge is then equal to

$$Q = Q_x + Q_w \qquad (2)$$

$$A = 0.5DT + 0.5WD_s \qquad (3)$$

$$T = W + T_x \qquad (4)$$

$$V = \tfrac{Q}{A} \qquad (5)$$

in which Q_w= capacity of gutter flow, Q_x= capacity of side flow, D = flow depth above gutter depression, W= gutter width, D_s= gutter depression, T_x= water spread width for side flow, A = flow area, and V = cross sectional average flow velocity. To achieve solutions for Eq's 1 and 2, the HEC 12 procedure recommends a design chart to accommodate the gutter depression. In fact, a gutter depression of 2 inches (5.0 cm) can significantly increase the interception capacity at an inlet, but has a diminishing increase on the SHCC as the water spread becomes wider. With D_s= 0, Eq 3 is reduced to

$$A = 0.5DT \tag{6}$$

$$D = TS_x \tag{7}$$

Aided by Eq's 1, 5, 6, and 7, the VD product is derived as:

$$VD = \frac{2K}{n}(TS_x)^{1.67}\sqrt{S_o} \tag{8}$$

and Eq 1 becomes:

$$Q = \frac{1}{2}(VD)T \tag{9}$$

Tables 1 and 2 present the differences in SHCC due to a 2-inch (5.0 cm) gutter depression for S_o=2% and S_o=5%. For both cases, the increase of SHCC due to a 2-inch (5.0 cm) depression on a 2-ft (0.61 m) gutter diminishes from 40.25% for 8-ft (2.44 m) water spread to 4.74% for 28-ft (8.54 m) water spread. During a storm event, Eq 9 can be an approximation for Eq 1 because of the wide water spread. As shown in Eq's 1 and 9, the major design parameter for determining the SHCC is the water spread which shall be the smaller of the available encroachment, T_m, into the traffic lanes and the available gutter depth, D_m. For instance, in a business district, the water depth in a gutter flow line shall not exceed the gutter height of six or eight inches and the water spread is limited to keep at least one traffic lane free from water for emergency uses. However, on a local or collector street, the water depth at the gutter flow line may be up to 6 inches (0.15 m) under a minor event and 12 inches (0.30 m) under a major event.

Water Spread Width Ft	With a 2-inch Gutter Depression				Without Gutter Depression				Percentage of Difference %
	Capacity cfs	Gutter Depth inch	Velocity fps	VD cfs/ft	Capacity cfs	Gutter Depth inch	Velocity fps	VD cfs/ft	
8.00	3.11	0.92	3.86	0.30	1.86	0.72	6.90	0.41	40.19
10.00	4.78	4.40	4.10	1.50	3.37	4.20	6.90	2.42	29.50
12.00	7.05	4.88	4.39	1.79	5.48	4.68	6.90	2.69	22.27
14.00	9.99	5.36	4.70	2.10	8.27	5.16	6.90	2.97	17.22
16.00	13.67	5.84	5.01	2.44	11.81	5.64	6.90	3.24	13.61
18.00	18.17	6.32	5.33	2.81	16.18	6.12	6.90	3.52	10.95
20.00	23.56	6.80	5.65	3.20	21.43	6.60	6.90	3.80	9.04
24.00	37.25	7.76	6.28	4.06	34.87	7.56	6.90	4.35	6.39
28.00	55.25	8.72	6.90	5.01	52.63	8.52	6.90	4.90	4.74

Table 1 Diminishing Impact of Gutter Depression on Street Conveyance for So=0.02 and Sx = 0.02

Water Spread Width ft	With a 2-inch Gutter Depression				Without Gutter Depression				Percentage of Difference %
	Capacity cfs	Gutter Depth inch	Velocity fps	VD cfs/ft	Capacity cfs	Gutter Depth inch	Velocity fps	VD cfs/ft	
8.00	4.92	3.92	6.10	1.99	2.93	1.92	10.91	1.75	40.45
10.00	7.57	4.40	6.48	2.38	5.32	2.40	10.91	2.18	29.72
12.00	11.15	4.88	6.94	2.82	8.67	2.88	10.91	2.62	22.27
14.00	15.79	5.36	7.43	3.32	13.07	3.36	10.91	3.05	17.23
16.00	21.62	5.84	7.93	3.86	18.67	3.84	10.91	3.49	13.64
18.00	28.73	6.32	8.43	4.44	25.58	4.32	10.91	3.93	10.96
20.00	37.25	6.80	8.94	5.07	33.89	4.80	10.91	4.36	9.02
24.00	58.90	7.76	9.94	6.43	55.14	5.76	10.91	5.24	6.38
28.00	87.35	8.74	10.90	7.94	83.21	6.74	10.91	6.13	4.74

Table 2 Diminishing Impact of Gutter Depression on Street Conveyance for So=0.05 and Sx = 0.02

Aided by Eq 7, the available depth, D_m, in a gutter can be converted to its water spread. The design parameter for determining the SHCC is selected as:

$$T = \min(T_m, \frac{D_m}{S_x}) \qquad (10)$$

Substituting Eq 10 into Eq 1 yields the SHCC.

STREET HYDRAULIC CAPACITY BY PERMISSIBLE VD PRODUCT

Design parameters for SHCC described in Eq 10 are based on gutter geometry and street classifications. In practice, such a SHCC is further subject to a reduction when safety becomes a concern. To reduce the risk of having flood flows with high velocities on the street, the reduction on a SHCC shall be proportional to the storm water conveyance capacity per unit width of the street and the momentum impulse associated with the gutter flow. According to Eq 9, the street storm water conveyance capacity, q, per unit width of water spread is:

$$q = \frac{Q}{T} = \frac{VD}{2} \qquad (11)$$

The momentum impulse of a gutter flow consists of both static and dynamic components. In comparison, the static force in a gutter flow is negligible because of the shallow depth. Aided by Eq's 8 and 9, the dynamic force, M, of a gutter flow is

$$M = \rho QV = \frac{\rho}{2S_x}(VD)^2 \qquad (12)$$

in which M = dynamic force, and ρ = density of water. Eq's 11 and 12 indicate that both unit storm water conveyance capacity and dynamic force in a gutter flow are proportional to its VD product. Design constraints on the water depth in the gutter or the spread on the street as described in Eq 10 do not reflect the impact of street slope. In fact, a reduction on the VD product can directly impose limits on both the unit-width capacity and the momentum impulse in a gutter flow. Although more research needs to be conducted to quantitatively correlate the VD products to safety issues or specifics, this study emphasizes the derivation of the general relationships among the VD product, ASHCC, and discharge reduction factors. Consider that the VD product of a gutter flow shall not exceed a limit defined by the safety considerations as

$$VD \le L \qquad (13)$$

in which L = permissible VD product. For instance, L= 6.0 cfs/ft (0.56 cms/m) is recommended by Clark County, Nevada for a 10-year event. According to Eq 11, it imposes a limit of 3.0 cfs per foot (0.28 cms per meter) of water spread or a gutter flow of 6.0 cfs (0.56 cms) carried within a 2-ft (0.61 m) gutter. The dynamic momentum carried by the flow section is confined to be no more than 1,728 pounds (0.86 tons) when S_x=0.02 ft/ft, and ρ = 1.92 slug/cubic ft (1000 kg/cubic m). Substituting Eq 13 into Eq 8 yields the permissible water spread, T_L , for the specified L as:

$$T_L \le \frac{1}{S_x}\left(\frac{nL}{2K\sqrt{S_o}}\right)^{0.6} \qquad (14)$$

By Eq 9, the ASHCC is equal to:

$$Q_L = \frac{1}{2}LT_L \qquad (15)$$

in which Q_L= allowable street hydraulic conveyance capacity (ASHCC). In current practice, the SHCC is firstly determined by Eq's 1 and 10 and then compared with Eq 13. If the VD product of the SHCC exceeds the value of L, the corresponding ASHCC is further determined by reducing the water spread until Eq 13 is satisfied. In this study, such a guessing process is replaced with Eq 14 which directly provides the limiting spread, T_L , for the specified L. Known T_L , Eq 10 can be revised as

$$T = \min\left(T_m, \frac{D_m}{S_x}, T_L\right) \tag{16}$$

Substituting the water spread by Eq 16 into Eq 1, the ASHCC can be obtained.

STREET HYDRAULIC CAPACITY BY DISCHARGE REDUCTION

In addition to the approach of permissible VD product, the discharge reduction method has also been recommended for street drainage designs. For instance, the City and County of Denver (1968) have adopted a set of reduction factors derived from field experience. These two co-existing approaches are not yet correlated and result in different predictions. In this study, the consistency between these two approaches was also investigated. By definition, a discharge reduction factor, R, is defined as:

$$R = \frac{Q_L}{Q} \tag{17}$$

Substituting Eq's 8, 9, 13, and 15 into Eq 17 yields

$$R = \frac{LT_L}{VDT} = \frac{1}{(TS_x)^{2.67}}\left[\frac{nL}{2K\sqrt{S_o}}\right]^{1.60} \qquad 0 \le R \le 1.0 \tag{18}$$

In application, the discharge reduction method begins with the determinations of the water spread, T, by Eq 10 and then the SHCC by Eq 1. Next, the discharge reduction factor can be derived by Eq 18 for the specified value of L. For a steep street, Eq 18 will result in R<1.0, indicating that the given design discharge shall be reduced. For a mild sloped street, Eq 18 will result in R>1.0, indicating that the street gutter can carry even more than the design discharge without exceeding the permissible VD product. Having determined the discharge reduction factor by Eq 18, the corresponding ASHCC can be directly obtained by Eq 17. Figure 2 was produced by Eq 18 to match with Denver's experience. Denver's discharge reduction curves can consistently match with the VD product approach when the street slope is steeper than 3%. It appears that Denver's experience for the ASHCC is approximately equivalent to L=1.0 cfs/ft (0.093 cms/m) applied to the SHCC determined by 13.5-ft (4.12 m) water spread for a minor event, and L=2.0 cfs/ft (0.186 cms/m) applied to the SHCC determined by 22.0-ft (6.71 m) water spread for a major event. Although there isn't any document to confirm the above assertion, both are reasonable when the street is designed to collect storm runoff between street inlets 300 feet (91.5 m) to 400 feet (122.0 m) apart.

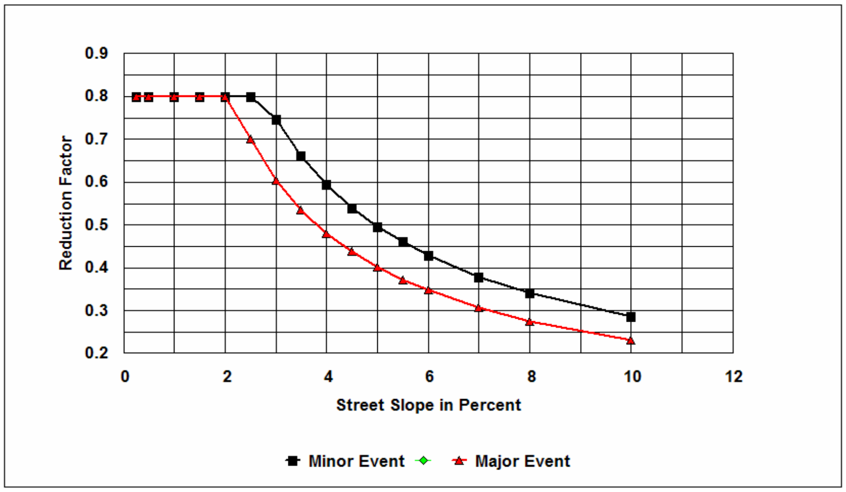

Figure 2. Discharge Reduction Factors for Minor and Major Events.

Selection of the permissible VD product depends on an over-all consideration among local climate, traffic safety, and street drainage planning. For instance, in an arid climate as the Las Vegas area in the State of Nevada, the annual rainfall depth of 4.0 inches (102 mm) is only distributed among two or three significant events in a year. The alternative of storm sewer systems is not economically favorable for such a no-base flow condition. As a result, the streets in the Las Vegas area are designed using higher permissible VD products to provide the additional function for storm water drainage. Flood proof walls of one to two feet tall are built along the streets and mingled with desert landscaping. During a storm event , a 20- to 30-ft (6.1- to 9.2-m) water spread on a 60 to 80-ft (18.3- to 24.4-m) street is a common practice in an arid region as the City of Las Vegas, Nevada. On the contrary, the annual precipitation is approximately 13.5 inches (343 mm) in the City of Denver, Colorado. Analysis of a 40-year record of the City of Denver indicates that the average interevent time is approximately 104 hours and 94% of rain storms produce a rainfall depth less than the 2-year one-hour event (Guo and Urbonas 1996). With such frequent nuisance flows on the streets, the City and County of Denver has set forth a drainage policy to efficiently collect the minor event by storm sewer and inlet systems. The streets in the Denver area only need to carry the amount of storm water intercepted between street inlets. As a result, lower permissible VD products have been recommended for street drainage designs.

CONCLUSION

Safety about storm water flowing on streets has been an increasing concern. This study investigates the rationality of the two co-existing approaches: (1) the VD product method, and (2) the discharge reduction method. Both methods are empirical and adopted for determining the street's allowable storm water conveyance capacity. In this study, the street hydraulic equation is re-arranged to express the unit-width SHCC and the flow momentum impulse as a function of the VD product in the gutter flow. The hyperbolic relationship of the VD product sets a control on the unit width discharge between flow velocity and depth. A higher permissible VD product results in a wider water spread and higher runoff conveyance capacity on the street. As a result, a limit on the VD product will directly confine the runoff discharge and runoff momentum impulse on the street.

Storm water drainage systems are designed by risk-based approaches. Inconsistent safety criteria will add uncertainties to the selected risk in terms of the frequency of the design event. It is important for street drainage designs that the permissible VD products are selected as a safety criterion based on traffic safety and the local drainage planning as to how the major and minor drainage systems are to be developed. In this study, the permissible VD product is further converted to its permissible water spread width beyond which a discharge reduction is required. With the re-arranged equation of street hydraulics, discharge reduction factors can be mathematically related to VD products. Therefore, a consistency between these two approaches has been established.

The current practice for determining the ASHCC involves a lengthy and iterative process. With the modifications developed in this study, the ASHCC can directly estimated by the water spread defined by Eq 16, or the reduction factor by Eq 18. This new procedure converts the current implicit procedure to an explicit procedure, and results in consistent predictions between the VD product and discharge reduction methods.

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