
A Simplified Approach for Quantifying Driving Rain on Buildings

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ABSTRACT

*A simplified approach for quantifying driving rain loads on building facades is presented. It is based on the well-known semi-empirical driving rain relationship (driving rain intensity = coefficient * wind speed * horizontal rainfall intensity). The coefficient in this relationship has often been assumed constant, but in reality it is a complicated function. For use in the simplified approach, this coefficient—as a function of building geometry, wind speed, wind direction, horizontal rainfall intensity—will be determined in advance by a set of numerical simulations with CFD (computational fluid dynamics). The resulting catalog with driving rain coefficients is then made available to users, and the simplified quantification approach consists of using these coefficients in combination with the driving rain relationship and standard weather data (wind speed, wind direction, horizontal rainfall intensity). In this paper, the philosophy of the simplified quantification approach is presented and illustrated for the case of a low-rise building.*

INTRODUCTION

Driving rain is one of the most important moisture sources affecting building facades. Information concerning the exposure to driving rain is essential to design building envelopes with a satisfactory hygrothermal performance. Knowledge on the quantity of driving rain that reaches building facades is also an essential requirement as a boundary condition for heat-air-moisture (HAM) transfer analysis. In the past, a number of methods have been employed to quantify driving rain amounts. Three categories are:

1. Experimental methods
2. Semiempirical methods
3. Numerical methods

The experimental approach consists of measuring driving rain with driving rain gauges. It has been the primary tool in driving rain studies and it has provided the basic knowledge that we have on driving rain. However, the drawbacks of this approach are numerous. Measurements are often impractical and difficult to carry out, driving rain is usually not measured

at meteorological stations, and databases of driving rain measurements are not commonly available. Furthermore, measurements usually only provide limited spatial and temporal information, and recent research efforts (Högberg et al. 1999; Blocken 2004) have illustrated that driving rain measurements can suffer from large errors (up to 100%, depending on the type of wind-driven rain gauge and the type of rain events).

The standard meteorological data measured at weather stations are wind speed, wind direction, and horizontal rainfall. As driving rain is usually not measured, it would be interesting if information on driving rain could be obtained from standard weather data. This idea drove researchers to establish semi-empirical relationships between driving rain and the influencing climatic parameters wind speed, wind direction, and horizontal rainfall. The development of these relationships was guided by the experimental observations that both the free driving rain (i.e., without buildings present) and the driving rain on buildings increase approximately proportionally with wind speed and horizontal rainfall. The relationships

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are semi-empirical in that their forms have theoretical bases but free parameters have been chosen to fit experimental data. Practically all existing semi-empirical methods are based on one of two approaches, both of which were initiated by Hoppestad (1955): the driving rain index and the driving rain relationship. In this paper, we will focus on the latter. In 1955, Hoppestad proposed the following relationship for the free driving rain intensity:

$$R_{dr} = \kappa \cdot U \cdot R_h \quad (1)$$

where R_{dr} is the driving rain intensity, U the wind speed, and R_h the horizontal rainfall intensity (the horizontal rainfall intensity is the rainfall intensity through a horizontal plane, as measured at weather stations). The relationship is written here in terms of intensity (rate of rainfall: $R - L/m^2 h$ or mm/h), but it can just as well be written in terms of amounts (sum of rainfall: $S - L/m^2$ or mm). Hoppestad called Equation 1 “the driving rain relationship” and the factor κ “the driving rain coefficient.” Values for κ were typically obtained by measurements with free-standing driving rain gauges. Later, Lacy (1965, 1977) refined Equation 1 by employing empirical relationships that express the median raindrop size as a function of rainfall intensity (Laws and Parsons 1943) and the terminal velocity of such raindrops (Best 1950a). This led to Equation 2:

$$R_{dr} = 0.222 \cdot U \cdot R_h^{0.88}, \quad (2)$$

where 0.222 (s/m) is the driving rain coefficient (average value) that results from the adopted empirical relationships. The exponent 0.88 can in good approximation be omitted — and this is almost always done:

$$R_{dr} \approx 0.222 \cdot U \cdot R_h \quad (3)$$

It is noted that Equation 3 yields the free driving rain, i.e., the driving rain passing through an imaginary vertical surface in an undisturbed airstream. It does not take into account local phenomena induced by the topography and by the building itself. The particular wind flow pattern around a building causes a deflection of wind and raindrop trajectories. As a result, the quantity of driving rain on buildings can widely differ from the free driving rain. Accounting for local effects was attempted by a relationship similar to Equation 3, using an adapted driving rain coefficient α instead of the free driving rain coefficient κ (Equation 4):

$$R_{dr} = \alpha \cdot U \cdot R_h \quad (4)$$

In order to take into account the effect of wind direction, the factor $\cos\theta$ is usually added:

$$R_{dr} = \alpha \cdot U \cdot R_h \cdot \cos\theta, \quad (5)$$

where θ is the angle between the wind direction and the line normal to the wall (multiplying with $\cos\theta$ corresponds to using the component of the wind speed normal to the wall).

The weakness of this semi-empirical method is the determination of the adapted driving rain coefficient, as the entire complexity of the interaction between driving rain and the building is to be integrated in this single value. Measurements by Lacy (1965), Ishizaki et al. (1970), Schwarz (1973), Sandin (1991), Henriques (1992), Flori (1992), Künzel (1993), Hens and Ali Mohamed (1994), Straube and Burnett (1997), and others indicate that driving rain coefficients vary considerably with the size of the building and show a large variation across the building facade: values from 0.02 s/m (9% of the free coefficient 0.222 s/m) to 0.26 s/m (120% of 0.222 s/m) have been found.

As research efforts employing experimental and semi-empirical methods continued to reveal the inherent complexity of the problem, researchers realized that further achievements were to be found through numerical simulation. Numerical simulation comprises the calculation of the wind flow pattern around the building by solving the complex three-dimensional Reynolds-averaged Navier-Stokes equations with a CFD code and the calculation of raindrop trajectories in this flow pattern (Sandberg 1974; Rodgers et al. 1974a, 1974b; Choi 1991, 1993, 1994a, 1994b; Blocken and Carmeliet 2000a, 2002). Recently, validation of the numerical simulation method has illustrated that accurate results can be obtained (Blocken and Carmeliet 2002; Blocken 2004). Numerical simulation has provided a new impulse in driving rain research. However, like the experimental and the semi-empirical approach, the numerical method also suffers from a number of drawbacks: the inherent complexity of conducting CFD simulations, the large amount of preparation work (constructing a digital model of the building and a suitable and accurate computational grid around it and searching appropriate injection positions for the raindrops), the long calculation times (easily up to several days on a dual Xeon 2.4 GHz workstation for three-dimensional simulations), and the large memory requirements (up to 3 GByte RAM for three-dimensional simulations). Furthermore, it is noted that further validation studies are needed. Up to now, extensive validation of the numerical driving rain results has been conducted for a low-rise building of complex geometry (Blocken and Carmeliet 2002; Blocken 2004). A good agreement between the experimental and the numerical results has been obtained for very different rain event types, and it has been shown that the numerical method is significantly more accurate and more reliable than the semi-empirical methods (driving rain relationship) (Blocken 2004). Although it is recognized that further validation efforts on different building configurations are needed, these research results provide a fairly strong indication that the numerical method will also be more accurate and more reliable for other building configurations. But, given the drawbacks listed above, it is clear that the numerical method, in spite of its better accuracy and its far-reaching possibilities, is not feasible for general and practical use in driving rain quantification.

The simplified quantification approach that is presented in this paper is an attempt to combine the accuracy and the power of the numerical approach with the ease of use of the simple driving rain relationship. Measurements and numerical simulations have shown that the driving rain coefficient α is a complicated function of wind speed, wind direction, and horizontal rainfall intensity and that it varies significantly over the building facade. To capture the complexity of this coefficient, we propose to determine it by numerical simulation. When this is done for a range of typical building configurations with different dimensions, a catalog of driving rain coefficients is obtained. This catalog will be made available to researchers and building designers. The simplified quantification approach then consists of selecting the appropriate driving rain coefficients from the catalog and inserting them into the simple driving rain relationship, together with standard weather data. For the selection of the coefficients, two options will be made available to the user. The first option consists of extracting the appropriate coefficients from the catalog and interpolating between these discrete values. The second option comprises the use of a fitted closed-form analytical formula for the driving rain coefficient, which provides more ease of use. In the present paper, the philosophy of the simplified quantification approach will be illustrated for the case of a low-rise building. Both options in the approach will be applied to estimate the spatial and temporal distribution of driving rain for a number of transient rain events. The paper starts with providing some brief notes on the numerical simulation method. Next, the two options to determine the driving rain coefficient are outlined. Finally, these options are applied and the results are compared.

NUMERICAL METHOD

The numerical simulation method comprises the following steps (Choi 1993, 1994a; Blocken and Carmeliet 2000a, 2002):

1. Calculate the steady-state wind flow pattern around the building with a CFD code.
2. Obtain raindrop trajectories in the flow pattern.
3. Determine the catch ratio from the configuration of the raindrop trajectories and the raindrop-size distribution. The catch ratio η is defined as the ratio of the driving rain (intensity R_{dr} or amount S_{dr}) to the horizontal rainfall (intensity R_h or amount S_h) (Equation 6):

$$\eta = \frac{R_{dr}}{R_h}; \quad \eta = \frac{S_{dr}}{S_h} \quad (6)$$

The catch ratio has six basic influencing parameters:

1. Building geometry (including environment topology)
2. Position on the building facade
3. Reference wind speed
4. Reference wind direction
5. Horizontal rainfall intensity
6. Raindrop-size distribution

The reference wind speed and wind direction refer to the magnitude and the direction of the horizontal wind velocity component at a height of 10 m above ground in the upstream undisturbed wind flow. These values are measured at standard meteorological stations together with the horizontal rainfall intensity. The raindrop-size distribution is difficult to measure (Salles et al. 1999). Such measurements are only performed exceptionally. Usually, empirical relationships are adopted for the raindrop spectrum (Marshall and Palmer 1948; Best 1950b; Mualem and Assouline 1986). For driving rain simulations, the formula of Best (1950b) is most often used. This choice is based on the extent of the study carried out by Best. It was supported by a wide bibliographical survey and measurements for a large number of rain events. The spectrum by Best provides a one-to-one relationship between the raindrop spectrum and the horizontal rainfall intensity (Figure 1). As a result, recalling the six influencing parameters of the catch ratio mentioned above, for a given building geometry and a fixed position on the building facade, the catch ratio is unambiguously defined by three parameters: the reference wind speed, the wind direction, and the horizontal rainfall intensity. Numerically calculated catch ratios have been provided by the current authors for the low-rise VLIET building (Blocken and Carmeliet 2002). The VLIET building is the test building of the Laboratory of Building Physics at the University of Leuven. Its geometry and dimensions are displayed in Figure 2. Catch ratios have been calculated for each of the seven positions on the southwest facade and for the southwest wind direction (perpendicular to the facade). The

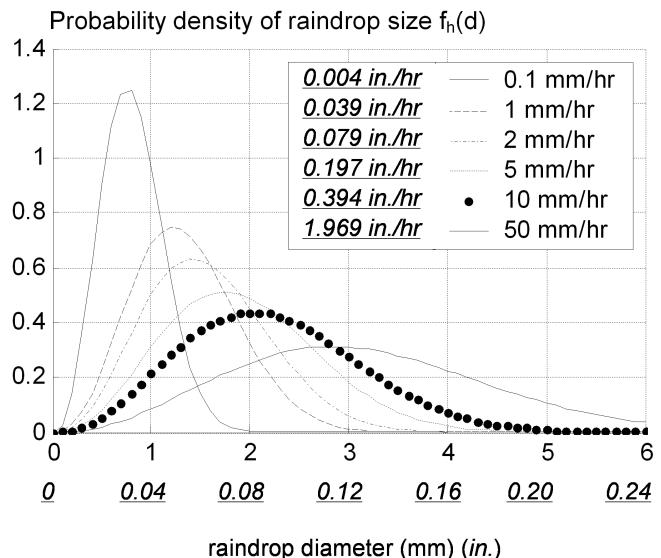


Figure 1 Raindrop-size distribution (in terms of water volume fraction) according to Best (1950b) with the horizontal rainfall intensity as a parameter. The raindrop spectrum exhibits a one-to-one relationship with the horizontal rainfall intensity.

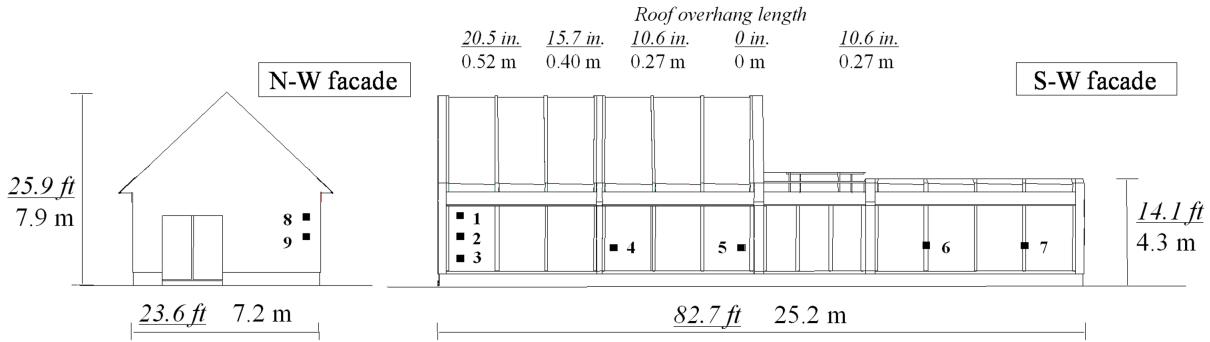


Figure 2 VLIET test building. Northwest and southwest facade. Building dimensions, including roof overhang length, and positions of the driving rain gauges (numbered 1 to 9).

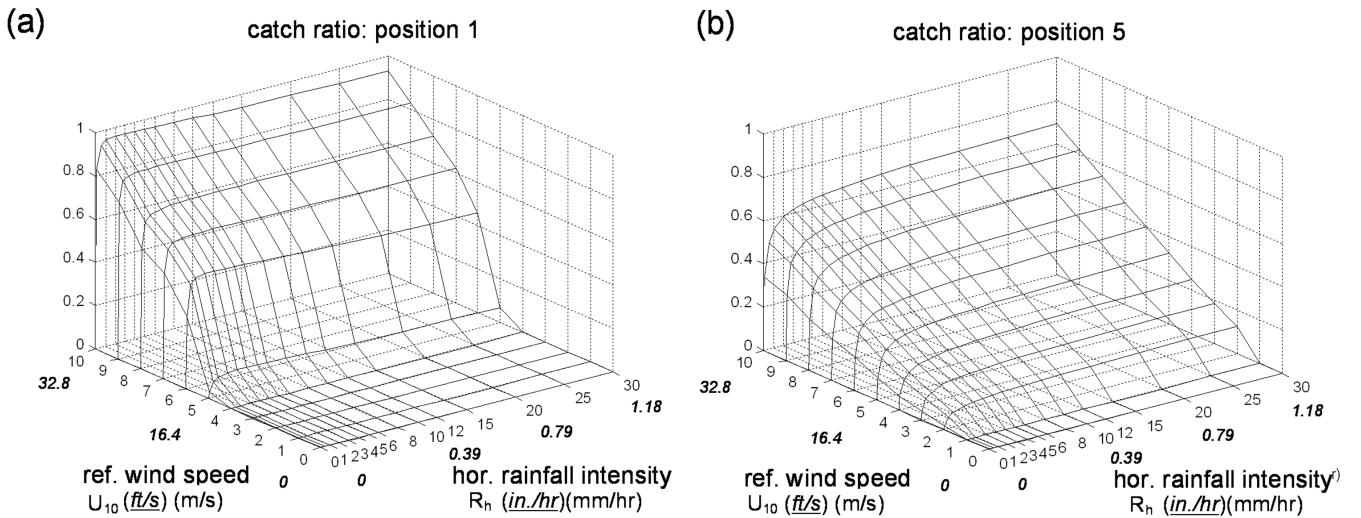


Figure 3 Numerically calculated catch ratio as a function of wind speed and horizontal rainfall intensity for positions 1 and 5 of the southwest facade of the VLIET building. The wind direction is perpendicular to the southwest facade.

catch ratio as a function of wind speed and horizontal rainfall intensity is typically displayed as three-dimensional surface plots. Figure 3 illustrates these plots for position 1 and position 5. From the catch ratio values, the driving rain coefficient is easily determined by dividing the catch ratio by the reference wind speed U (see Equations 4 and 6):

$$\alpha = \frac{R_{dr}}{U \cdot R_h} = \frac{\eta}{U} \quad (7)$$

Three-dimensional plots of the driving rain coefficient are given in Figure 4. The following observations are made:

- Below a certain wind speed value, the driving rain coefficient suddenly drops to zero. This wind speed threshold is 6 m/s for position 1 and 2 m/s for position 5. The reason is that below these thresholds, these positions of the facade are sheltered from rain by the roof overhang (Figure 2). Posi-

tion 1 is situated just below the largest roof overhang, which explains the large threshold value found here.

- For the lowest horizontal rainfall intensities, the driving rain coefficient steeply increases with increasing intensity. For the higher intensities, it changes only slightly with intensity (a slight decrease at position 1 and a slight increase at position 5).
- At first sight, the influence of wind speed above the shelter threshold appears to be rather small. However, the curvature of the “driving rain coefficient – horizontal rainfall intensity” curves and the position of this curvature are wind speed-dependent, as will be discussed in the next section.

THE SIMPLIFIED QUANTIFICATION APPROACH

The simplified quantification approach consists of inserting appropriate driving rain coefficients into the driving rain

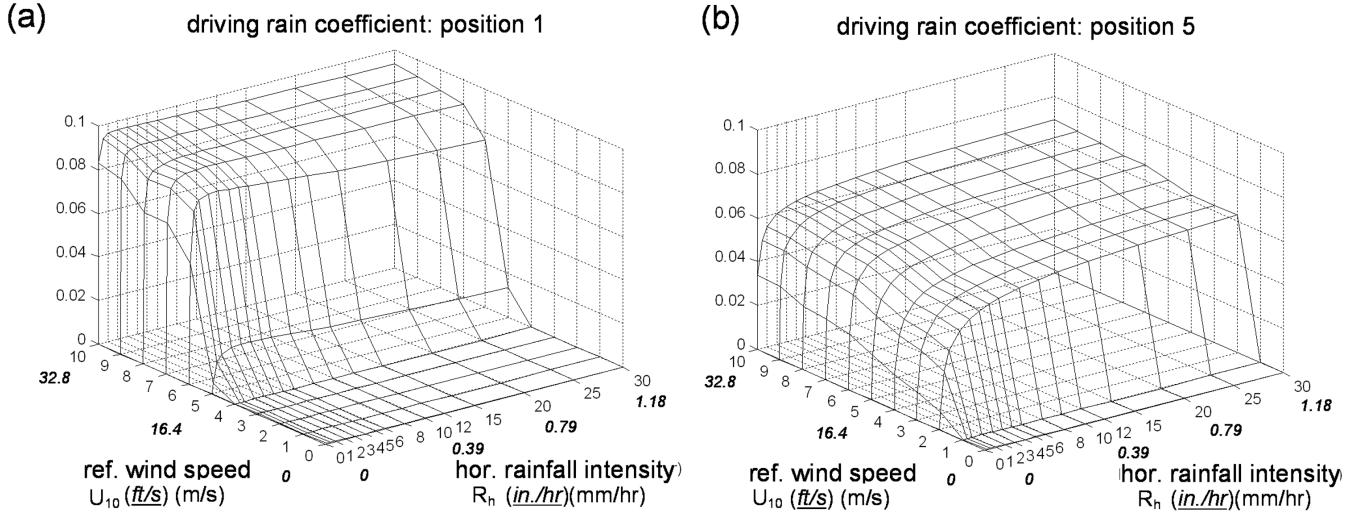


Figure 4 Numerically calculated driving rain coefficient as a function of wind speed and horizontal rainfall intensity for positions 1 and 5 of the southwest facade of the VLIET building. The wind direction is perpendicular to the southwest facade.

relationship (Equations 4 and 5). For the user of the approach, two options are available to obtain these coefficients:

1. Driving rain coefficient data tables
2. Driving rain coefficient formula

Driving Rain Coefficient Data Tables

The first option consists of extracting the driving rain coefficients from data tables. These data tables are constructed by directly drawing the coefficients from the corresponding three-dimensional plots (Figure 4). Tables 1 and 2 contain the driving rain coefficients for positions 1 and 5 of the VLIET building, for the southwest wind direction. Values are provided for a discrete series of wind speeds and horizontal rainfall intensities. Intermediate values can be obtained by linear interpolation.

Driving Rain Coefficient Formula

To avoid the necessity of interpolating the driving rain coefficient, we have determined a closed-form analytical formula that describes the part of the three-dimensional surface “ $\alpha = F(U, R_h)$ ” above the threshold wind speed mentioned earlier (6 m/s for position 1 and 2 m/s for position 5). The formula has been fitted to the surface by multiple applications of the least-squares method. The methodology that has been used to find this formula is briefly given below.

In a first step, the function describing the relationship between the driving rain coefficient α and the horizontal rainfall intensity R_h is determined for each wind speed value separately. The functions all have the form,

$$\alpha = \frac{A \cdot R_h}{B + R_h} . \quad (8)$$

The values for A and B are determined by the least-squares method. Different values for A and B are found at different wind speeds. The value of A corresponds to the value of the driving rain coefficient for high R_h . It describes the “altitude” of the plateau of the three-dimensional surface (Figure 4). It is an approximately linear function of wind speed (above the threshold speed). The term B determines the curvature and the position of maximum curvature of the curve “ $\alpha - R_h$ ”. It is an inverse function of wind speed. The following functions are introduced to describe A and B :

$$A = C + D \cdot U \quad (9)$$

$$B = \frac{E}{F + U} \quad (10)$$

The coefficients C , D , E , and F are constants. Combining equations 8, 9, and 10 yields the following formula for the driving rain coefficient:

$$\alpha = \left(\frac{aU^2 + bU + c}{R_h U + dR_h + e} \right) R_h \quad (11)$$

where the coefficients a , b , c , d , and e are linear combinations of C , D , E , and F . The driving rain relationship then takes the form,

$$R_{dr} = \left(\frac{aU^2 + bU + c}{R_h U + dR_h + e} \right) \cdot U \cdot R_h^2 . \quad (12)$$

Table 1. Driving Rain Coefficients for the Low-rise VLIET Building: Position 1, Wind Direction is Southwest (225°)

R _h (in./h)	(mm/h)	U ₁₀ (m/s) (ft/s)										
		0	3.28	6.56	9.84	13.12	16.40	19.69	22.97	26.25	29.53	32.81
0.00	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.00	0.1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0049	0.0554	0.0689	0.0696	0.0801	0.0829
0.02	0.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0139	0.0786	0.0847	0.0841	0.0909	0.0937
0.04	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0171	0.0831	0.0879	0.0873	0.0928	0.0956
0.08	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0191	0.0849	0.0896	0.0893	0.0936	0.0962
0.12	3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0194	0.0849	0.0901	0.0901	0.0937	0.0962
0.16	4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0194	0.0846	0.0903	0.0905	0.0937	0.0960
0.20	5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0191	0.0842	0.0903	0.0907	0.0936	0.0958
0.24	6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0188	0.0837	0.0903	0.0908	0.0936	0.0956
0.31	8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0182	0.0829	0.0901	0.0909	0.0934	0.0952
0.39	10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0176	0.0820	0.0900	0.0909	0.0932	0.0949
0.47	12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0170	0.0813	0.0898	0.0909	0.0931	0.0946
0.59	15	0.0000	0.0000	0.0000	0.0000	0.0000	0.0162	0.0803	0.0896	0.0908	0.0929	0.0943
0.79	20	0.0000	0.0000	0.0000	0.0000	0.0000	0.0151	0.0790	0.0892	0.0906	0.0926	0.0938
0.98	25	0.0000	0.0000	0.0000	0.0000	0.0000	0.0143	0.0779	0.0889	0.0905	0.0923	0.0934
1.18	30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0135	0.0770	0.0887	0.0903	0.0921	0.0931

Table 2. Driving Rain Coefficients for the Low-rise VLIET Building: Position 5, Wind Direction is Southwest (225°)

R _h (in./h)	(mm/h)	U ₁₀ (m/s) (ft/s)										
		0	3.28	6.56	9.84	13.12	16.40	19.69	22.97	26.25	29.53	32.81
0.00	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.00	0.1	0.0000	0.0000	0.0079	0.0126	0.0154	0.0202	0.0253	0.0271	0.0288	0.0330	0.0337
0.02	0.5	0.0000	0.0000	0.0261	0.0307	0.0330	0.0377	0.0425	0.0443	0.0461	0.0488	0.0492
0.04	1	0.0000	0.0000	0.0347	0.0384	0.0401	0.0445	0.0489	0.0504	0.0522	0.0543	0.0547
0.08	2	0.0000	0.0000	0.0426	0.0452	0.0465	0.0504	0.0544	0.0556	0.0573	0.0589	0.0593
0.12	3	0.0000	0.0000	0.0468	0.0488	0.0498	0.0535	0.0571	0.0581	0.0597	0.0612	0.0616
0.16	4	0.0000	0.0000	0.0495	0.0511	0.0519	0.0555	0.0589	0.0598	0.0613	0.0627	0.0630
0.20	5	0.0000	0.0000	0.0514	0.0528	0.0535	0.0570	0.0602	0.0609	0.0624	0.0637	0.0640
0.24	6	0.0000	0.0000	0.0529	0.0541	0.0547	0.0581	0.0611	0.0618	0.0632	0.0645	0.0648
0.31	8	0.0000	0.0000	0.0551	0.0560	0.0565	0.0597	0.0625	0.0630	0.0644	0.0655	0.0659
0.39	10	0.0000	0.0000	0.0567	0.0573	0.0577	0.0608	0.0635	0.0639	0.0653	0.0663	0.0667
0.47	12	0.0000	0.0000	0.0578	0.0584	0.0587	0.0617	0.0643	0.0645	0.0659	0.0668	0.0672
0.59	15	0.0000	0.0000	0.0592	0.0595	0.0598	0.0626	0.0651	0.0653	0.0666	0.0674	0.0679
0.79	20	0.0000	0.0000	0.0607	0.0609	0.0611	0.0637	0.0661	0.0661	0.0674	0.0681	0.0686
0.98	25	0.0000	0.0000	0.0618	0.0618	0.0620	0.0645	0.0667	0.0667	0.0679	0.0685	0.0690
1.18	30	0.0000	0.0000	0.0626	0.0625	0.0627	0.0651	0.0672	0.0671	0.0683	0.0688	0.0694

Table 3. Constants for the Driving Rain Coefficient Formula and Corresponding Correlation Coefficient for Each of the 7 Positions at the Southwest Facade of the Low-Rise VLIET Building, Wind Direction is Southwest (225°)

position	a	b	c	d	e	r ²
1	0.00203	0.06784	-0.26468	-3.529	0.109	0.996
2	0.00250	0.05340	-0.21328	-3.440	0.211	0.998
3	0.00188	0.05341	-0.14187	-2.446	0.372	0.993
4	0.00125	0.05146	-0.06551	-1.236	1.359	0.992
5	0.00067	0.05990	-0.00888	-0.148	1.584	0.992
6	0	0.07200	0.11678	1.622	1.849	0.991
7	0.00049	0.07493	-0.01148	-0.153	0.694	0.996

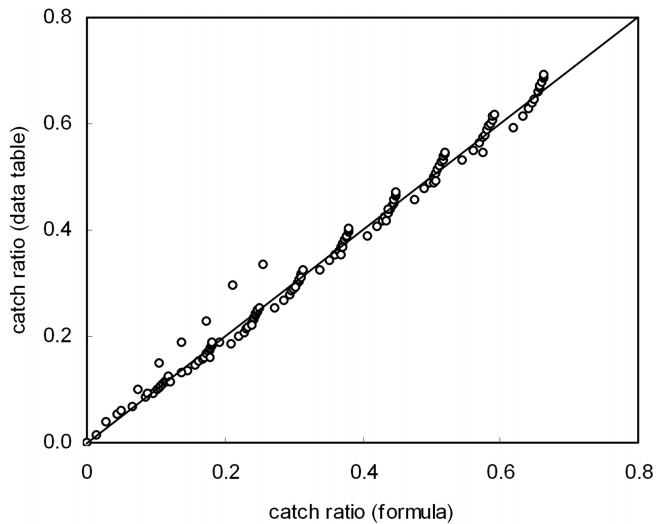


Figure 5 Correlation between the “exact” driving rain coefficients (as provided in Table 2) and the approximate coefficients (obtained with the driving rain coefficient formula) for position 5 on the southwest facade.

The values a to e are constants for a given position on the building facade and for a given wind direction. Their values for all seven positions at the southwest facade of the VLIET building and for southwest wind direction are given in Table 3. The table also provides the correlation coefficient, indicating the high correlation between the driving rain coefficients (or catch ratios) obtained using the formula and the original (data table) driving rain coefficients (or catch ratios) (see Table 1 and 2). Figure 5 illustrates this correlation for position 5. The outliers in this graph all concern the horizontal rainfall intensity $R_h = 0.1 \text{ mm/h}$ and high wind speed values. The fit at this value is less accurate because of the large steepness of the surface at low horizontal rainfall intensities and high wind speed (Figure 3b). Please note that the catch ratio is presented in this graph (i.e., the product of the driving rain coefficient and the wind speed).

A small drawback of the formula—in the case of the VLIET building—is the fact that it does not take into account the shelter effect by roof overhang. As a result, it only applies to the part of the surface above the wind speed shelter thresholds. Therefore, in order to be able to use this formula in this kind of situation, apart from the five coefficients a to e , the threshold value for each facade position should also be specified. In applying the formula for positions 1 and 5, below 5 m/s and 1 m/s, respectively, the driving rain coefficient should be set to zero. In between 5 and 6 m/s and between 1 and 2 m/s, the driving rain coefficient can, e.g., be set to half the value it would have at 6 m/s and 2 m/s, respectively. This drawback is only present here due to the fact that the building has a large overhang length compared to the height of the facade. For high-rise, medium-rise, and low-rise buildings without roof overhangs, this drawback disappears and Equations 11 and 12—with appropriate constants—will describe the entire surface of the three-dimensional plot.

Application of the Approach for Transient Rain Events

In practical applications, one will generally want to determine driving rain amounts for specific meteorological data records. Let us focus on Figure 6, which illustrates a data record for a transient rain event. To determine the driving rain amount for this rain event, the driving rain relationship is applied for every time step for which data are available (in the figure, 10-minute steps). It is important to note that the time interval of the input data should be short enough to capture the major fluctuations and peaks in wind speed, wind direction, and horizontal rainfall intensity. Earlier studies (Blocken and Carmeliet 2000b) have shown that the use of 10-minute data can provide accurate results, but that the use of hourly and certainly daily data can lead to significant underestimations of the driving rain amount.

When extracting the driving rain coefficient from the data tables, the user will have to perform interpolation between the discrete data values. The advantage of the driving rain coefficient formula is that the driving rain for a given position can be directly calculated. This formula can, e.g., be directly built into HAM simulation software.

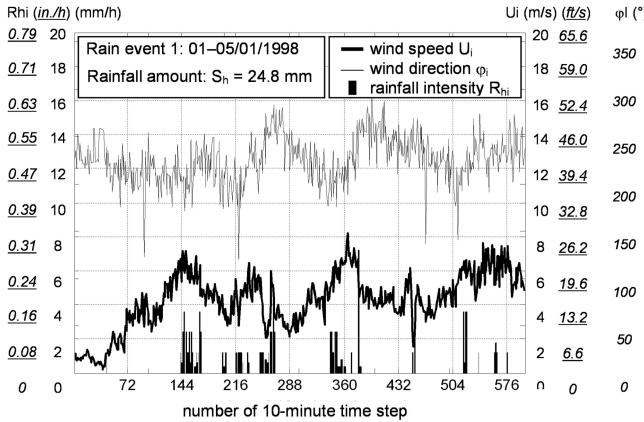


Figure 6 Measurements of wind speed U_i , wind direction ϕ_i , and horizontal rainfall intensity R_{hi} for each 10-minute interval in the rain event from 01 to 05/01/1998. Total horizontal rainfall amount: $S_h = 24.8 \text{ mm}$ (0.98 in.). Wind direction during rain is approximately southwest (225°).

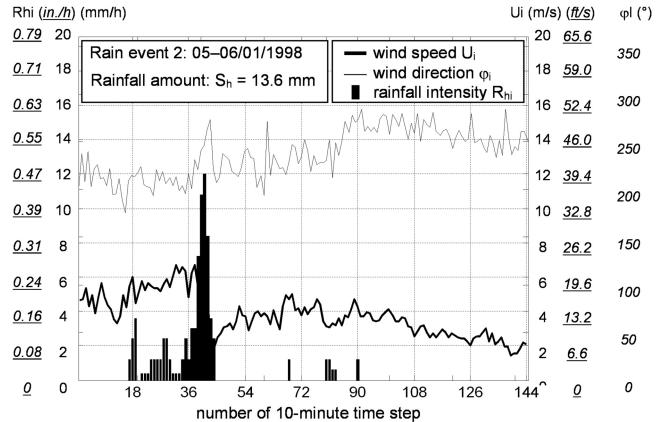


Figure 7 Measurements of wind speed U_i , wind direction ϕ_i , and horizontal rainfall intensity R_{hi} for each 10-minute interval in the rain event from 05 to 06/01/1998. Total horizontal rainfall amount: $S_h = 13.6 \text{ mm}$ (0.54 in.). Wind direction during rain is approximately southwest (225°).

APPLICATION AND VALIDATION

Both options of the simplified quantification approach are applied to determine the driving rain amount at different positions of the low-rise VLIET building for a number of on-site recorded rain events. It is noted that the use of the driving rain coefficient data tables in combination with the driving rain relationship will yield exactly the same results as the numerical quantification method employed earlier (Blocken and Carmeliet 2000a, 2002), as also at that time linear interpolation between the discrete data values was employed. The use of the driving rain coefficient formula will provide an approximation of this numerical solution.

Figures 6, 7, and 8 show three different rain events. Wind speed, wind direction, and horizontal rainfall intensity have been measured at the site of the VLIET building on a 10-minute basis. The wind direction during rain is approximately southwest (perpendicular to the facade). Table 4 compares the calculated driving rain amounts at all seven positions with each other and with the corresponding driving rain measurements. The values are those calculated/measured at the end of each rain event.

Let us first focus on the difference between both options in the calculation. In general, the agreement between both sets of results is satisfactory, except at position 1. This is due to two reasons: (1) the shelter by roof overhang, which is largest for this position, and (2) the fact that in the second option, the driving rain coefficient for wind speeds just below the shelter threshold value has been set to half the value it would have at the threshold wind speed, while in the first option, linear interpolation is employed.

Comparing the calculated driving rain amounts with the measurements, large discrepancies are observed at the first

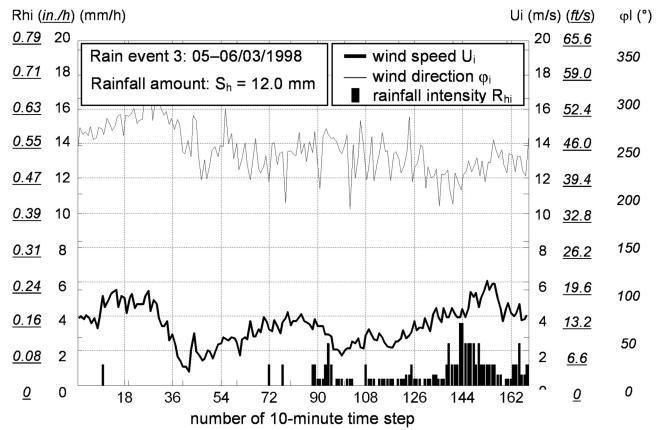


Figure 8 Measurements of wind speed U_i , wind direction ϕ_i , and horizontal rainfall intensity R_{hi} for each 10-minute interval in the rain event from 05 to 06/03/1998. Total horizontal rainfall amount: $S_h = 12.0 \text{ mm}$ (0.47 in.). Wind direction during rain is approximately southwest (225°).

two positions for all rain events. This is again due to the shelter effect of the large 0.52 m (20.5 in.) roof overhang above these positions: modeling the effect of roof overhang, even with a tool as powerful as CFD, is not easy. It is particularly difficult to determine the exact position of the transition region between the completely dry and the completely wet part of the facade, as discussed in Blocken and Carmeliet (2002). At the other positions, a satisfactory/good agreement is found, especially for rain events 2 and 3.

Table 4a. Comparison of Measured (Exp.) and Calculated (with the Data Tables and with the Driving Rain Coefficient Formula) Driving Rain Amounts (mm) for the Rain Events Displayed in Figures 6, 7, and 8*

		Driving rain amount (mm)						
position		1	2	3	4	5	6	7
Rain event 1	exp.	3.0	5.5	6.4	(-)	(-)	6.9	9.7
	data tables	7.6	8.7	7.6	6.2	6.7	7.7	9.0
	formula	6.7	9.1	8.0	6.4	7.0	8.1	9.3
Rain event 2	exp.	1.5	3.0	3.3	3.3	(-)	3.9	4.9
	data tables	2.5	3.9	3.7	3.1	3.4	4.0	4.5
	formula	2.0	3.9	3.7	3.1	3.5	4.1	4.6
Rain event 3	exp.	0.5	1.7	2.2	(-)	1.9	2.8	3.6
	data tables	0.8	2.4	2.3	1.9	2.1	2.6	3.1
	formula	0.6	2.7	2.5	2.0	2.3	2.8	3.2

* (-) indicates that no accurate measurements could be made due to equipment defect.

Table 4b. Comparison of Measured (Exp.) and Calculated (with the Data Tables and with the Driving Rain Coefficient Formula) Driving Rain Amounts (in.) for the Rain Events Displayed in Figures 6, 7, and 8*

		Driving rain amount (in.)						
position		1	2	3	4	5	6	7
Rain event 1	exp.	<u>0.12</u>	<u>0.22</u>	<u>0.25</u>	(-)	(-)	<u>0.27</u>	<u>0.38</u>
	data tables	<u>0.30</u>	<u>0.34</u>	<u>0.30</u>	<u>0.24</u>	<u>0.26</u>	<u>0.30</u>	<u>0.35</u>
	formula	<u>0.26</u>	<u>0.36</u>	<u>0.31</u>	<u>0.25</u>	<u>0.28</u>	<u>0.32</u>	<u>0.37</u>
Rain event 2	exp.	<u>0.06</u>	<u>0.12</u>	<u>0.13</u>	<u>0.13</u>	(-)	<u>0.15</u>	<u>0.19</u>
	data tables	<u>0.10</u>	<u>0.15</u>	<u>0.15</u>	<u>0.12</u>	<u>0.13</u>	<u>0.16</u>	<u>0.18</u>
	formula	<u>0.08</u>	<u>0.15</u>	<u>0.15</u>	<u>0.12</u>	<u>0.14</u>	<u>0.16</u>	<u>0.18</u>
Rain event 3	exp.	<u>0.02</u>	<u>0.07</u>	<u>0.09</u>	(-)	<u>0.07</u>	<u>0.11</u>	<u>0.14</u>
	data tables	<u>0.03</u>	<u>0.09</u>	<u>0.09</u>	<u>0.07</u>	<u>0.08</u>	<u>0.10</u>	<u>0.12</u>
	formula	<u>0.02</u>	<u>0.11</u>	<u>0.10</u>	<u>0.08</u>	<u>0.09</u>	<u>0.11</u>	<u>0.13</u>

* (-) indicates that no accurate measurements could be made due to equipment defect.

Figures 9, 10, and 11 illustrate the temporal distribution of the calculated and measured driving rain amount during the rain events at position 7. It is clear that the highest driving rain amounts occur during the co-occurrence of high wind speed and horizontal rainfall intensity. The correspondence between both calculations on one hand and between the calculations and the measurements on the other is good. The main reason is that position 7—as well as positions 3, 4, 5, and 6—is only slightly sheltered by a 0.27 m (10.6 in.) overhang (Figure 2).

DISCUSSION

The intent of this paper was only to present the philosophy of the simplified quantification approach. The construction of the catalog with driving rain coefficients and constants for the driving rain coefficient formula is currently in progress. A large set of numerical simulations is being performed for

different building configurations (among which are a high-rise slab, a high-rise tower building, a medium-rise long slab, and several types of low-rise buildings). For each of these buildings, a number of positions (typically nine) at the windward facade are selected at which driving rain coefficients are determined. The positions are evenly distributed over the facade, in such a way as to include at least the building facade corners, positions at the top and side edges, and at the middle of the facade (where, respectively, the highest, high, and lower driving rain amounts are expected). The catalog will be made available to researchers and building designers, which will allow them to use the driving rain relationship to easily and quickly obtain estimates of the driving rain amount on buildings of similar geometry. It is noted that the approach is “simplified” for the user but that the construction of the catalog is a huge engineering task.

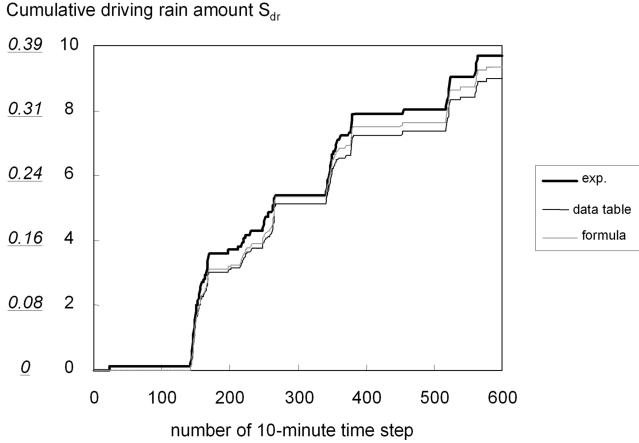


Figure 9 Temporal distribution of the cumulative driving rain amount S_{dr} at position 7 for the rain event displayed in Figure 6. Measured and calculated (with data tables and with driving rain coefficient formula) driving rain amount.

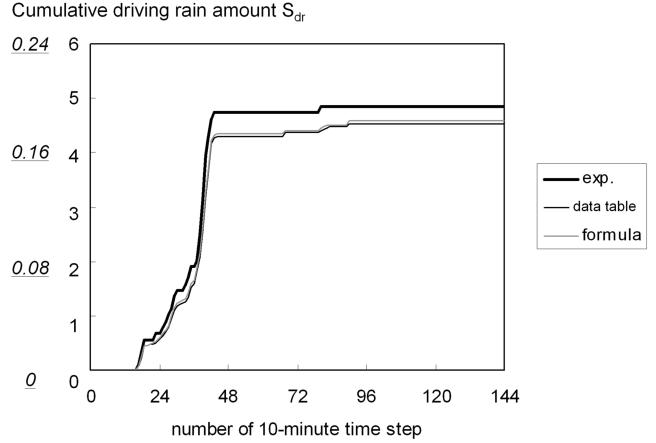


Figure 10 Temporal distribution of the cumulative driving rain amount S_{dr} at position 7 for the rain event displayed in Figure 7. Measured and calculated (with data tables and with driving rain coefficient formula) driving rain amount.

It is recognized that the simplified approach has its limitations. One will have to abandon this approach and resort to full numerical simulation in the following cases:

1. For buildings of complex geometry that cannot be classified under one of the configurations for which driving rain coefficients are made available (e.g., buildings with large roof overhang, buildings with rounded shapes, etc.)
2. For buildings that are sheltered by upstream obstacles (trees, other buildings, etc.)
3. When more detailed driving rain information is needed (e.g., the complete wetting pattern across a facade—catch ratios or driving rain coefficients—at every facade position)

Despite these limitations, it is believed that the simplified quantification approach will be useful:

1. To replace the often very simplified and, hence, inaccurate driving rain formulations in the current heat-air-moisture transfer software
2. To provide realistic estimates of driving rain on various types of buildings
3. To provide realistic values of driving rain intensities for water penetration tests for wall cladding assemblies, etc.

The study in this paper was limited to a single wind direction, perpendicular to the facade. The usual way to take into account varying wind direction in the driving rain relationship is to multiply the wind speed with the factor $\cos\theta$ as in Equation 5. This is an approximation and an additional error source. The CFD studies for constructing the catalog will include simulations of driving rain for different wind directions to provide wind-direction-dependent driving rain coefficients.

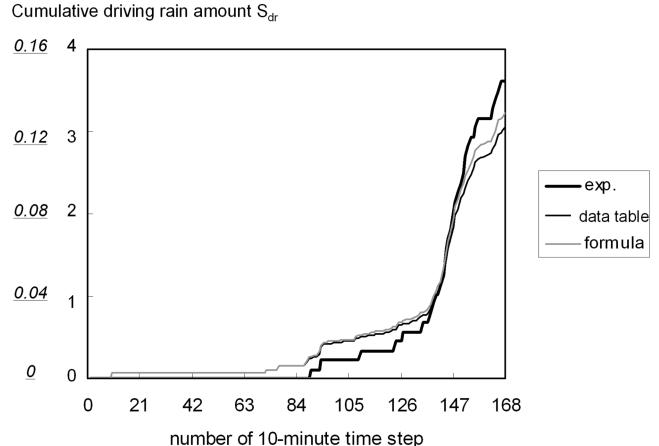


Figure 11 Temporal distribution of the cumulative driving rain amount S_{dr} at position 7 for the rain event displayed in Figure 8. Measured and calculated (with data tables and with driving rain coefficient formula) driving rain amount.

This will also allow us to investigate the magnitude of the error that is introduced by using the “ $\cos\theta$ ” assumption.

The driving rain coefficients that are used in the simplified approach are based on numerical simulations. The reliability of these simulations hence determines the reliability of the driving rain coefficients. Up to now, and to the knowledge of the current authors, validation of driving rain simulations on full-size buildings has only been performed in two cases: for the high-rise main building at Eindhoven University of Tech-

nology (van Mook 1999, 2002) and for the low-rise VLIET building at the University of Leuven (Blocken and Carmeliet 2000a, 2000b, 2002; Blocken 2004). Additional validation efforts will be necessary for other building configurations, which, in turn, will require additional driving rain measurements. It is stressed that driving measurements for validation require the simultaneous measurement of standard weather data (wind speed, wind direction, horizontal rainfall intensity) at the building site.

Standard weather data are measured at official meteorological stations and at private stations of companies and research laboratories. This provides the input data needed in the driving rain relationship. This way, accurate driving rain estimates at such stations can be obtained, which can be used in, e.g., HAM modeling. In general, however, standard weather data are not available at the building site. In this case, it has to be obtained by transforming data from a meteorological station, which can easily be several tens or hundreds of kilometers away, to the location of interest. Procedures to perform this transformation for the wind speed and wind direction exist, but they inevitably introduce additional errors (Bottema 1993; De Wit et al. 2002; Blocken et al. 2003). The transformation of rainfall data is most problematic, as rainfall is a local phenomenon and can show very large variations from one location to another, even on very small spatial scales. This poses an additional limitation on the practical use of all driving rain quantification approaches (except the experimental one) when there is no nearby weather station.

CONCLUSIONS

Three general methods have been used in the past to determine driving rain amounts on buildings: (1) the experimental method, (2) the semi-empirical method, and (3) the numerical method. The experimental method is not feasible as a general and practical tool, but it is vital to provide validation data for the semi-empirical and the numerical methods. The semi-empirical method is based on the well-known relationship between driving rain, wind speed, and horizontal rainfall (driving rain = coefficient * wind speed * horizontal rainfall). The major drawback in using this relationship is the fact that the coefficient is not a constant, as is usually assumed. It is a complicated function of space and time. The numerical method consists of CFD simulations to determine the driving rain amount on building models. It is a very powerful method, but it is also very time consuming and labor-intensive. Therefore, like the experimental and semi-empirical methods, it is not suitable for general use to predict driving rain amounts on buildings.

This paper has suggested a simplified approach for quantifying driving rain. It is based on the driving rain relationship mentioned above. But unlike earlier values, the driving rain coefficient in this relationship is not estimated by measurements but is now determined by numerical simulation/calculation. This approach has been illustrated for the case of a low-rise building. The driving rain coefficients have been provided

in tabular form. In addition, a closed-form analytical formula for the driving rain coefficient has been obtained. This provides two options for the user: (1) extract the driving rain coefficient from the tables or (2) evaluate the driving rain coefficient formula with the appropriate sets of constant coefficients. Both options in the simplified approach have been applied to determine the driving rain amounts on various positions on a low-rise building. The comparison of these results with measurements has shown that satisfactory results can be obtained and that the analytical formula closely fits the discrete tabulated driving rain coefficients.

In the future, the applicability of the simplified approach will be extended by the publication of the catalog providing driving rain coefficients and sets of constants for different building geometries. It is hoped that researchers and building designers will find this simplified approach useful to obtain their estimates of the driving rain amount on buildings.

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