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RAIN CATCH UNDER WIND AND VEGETAL COVER EFFECTS

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Abstract Wind effects on a rain gage can cause a significant underestimation of rainfall depths and contribute to the inconsistency in rainfall data. To reconstruct rainfall data requires a consistent method to quantify the undercatch. Although some empirical adjustment factors have been recommended, they are not generalized enough to reflect the variations of wind speed with respect to height. This paper presents a model by which the undercatch at an elevated rain gage can be estimated by the logarithmic wind velocity profile and raindrop terminal velocity. Deficiency percentages of rain catch predicted by this model agree with field observations and recommended adjustment factors. This approach was further expanded to predict rain undercatch percentage due to vegetal coverage or other obstructions.

Key Words *Undercatch, Rain, Gage, Wind*

INTRODUCTION

As stated in the Field Manual for Research in Agriculture Hydrology (Brakensiek et. al. 1979), wind speed and vegetal cover have been recognized as the major contributing factors to the inconsistency in rainfall data. Turbulence produced by winds around a rain gage can result in a highly varied precipitation pattern which reduces the rain amount captured by the orifice opening (Napor and Sevruk, 1999). Undercatchment by rain gages has been observed and studied since 1850. For instance, Symons (1866, 1880) reported that a 6-meter elevated rain gage caught approximately 85% of the rainfall amount received on the ground, and a rain gage installed on a church roof top of 45 meters above the ground experienced as much as a 50% undercatch. Operations of a rain gage during a storm involve many variables. Data inconsistency can be introduced by inadvertent gage operations, but interference by wind at the gage site is inevitable. For instance, during the January 9-10, 1995 rain storms in Sacramento, California, winds were in the range of 35 to 75 kilometers per hour for several hours (Curtis and Hymphrey 1995). Consistent rainfall records are the most significant input to a hydrologic analysis. Often, rainfall records are not adequately scrutinized to the degree necessary to develop a reliable data base (Curtis and Burnash, 1996). Without proper corrections, raw data from rain gages tend to underestimate the actual rainfall amounts and lead to less accurate hydrologic analyses and underestimated flood predictions. For example, approximately half of the difference between observed and simulated runoff peaks was due to rainfall-sampling errors (Michaud 1994). Current practices on the reconstruction of rainfall data rely on empirical adjustment factors. For instance, Larson and Peck (1974) reported that the undercatch percentages for an unshielded rain gage increases at about 1.0 % per every mile/hr or 2.2 % per every meter/second of wind speed. Gage catch correction factor has been implemented in the Sacramento ALERT program (Curtis and Humphrey 1995). Two sets of undercatch rates were developed: one for gage height and the other for wind speed (Gray 1973, Sevruk 1982). Often, rain gages in a network operate at various heights and are subject to different wind speeds. There is no guidance whether these two adjustment factors should be additive or multiplied when both gage height and wind speed are taken into consideration.

To improve the consistency in rainfall data, this paper provides a systematic approach that takes wind speed, gage height, and canopy effects into consideration when correcting for gage undercatch. The systematic approach only requires basic information that is generally available from most monitoring systems.

RAIN GAGE CATCH AFFECTED BY WIND SPEED

Operational errors of a rain gage can result from evaporation from the receiver, adhesion on the funnel surface, inclination and size of the orifice, raindrop splash etc.. The height of the rain gage orifice above the ground varies greatly. In general, orifice height is approximately 1 to 1.5 meter above the ground to avoid vegetal canopy. Variations of rainfall catch with respect to height were quantified from many field measurements by Symons (1880), and from experimental rain gage networks by Kurtyka et al. (1953). Using a gage with an orifice at 0.30 meter above the ground as a reference, a gage with an orifice at 6 meters above the ground would have a 10% undercatch, and a gage with an orifice at 5 centimeters above the ground would have a 2% overcatch. In order to minimize wind effects, 45-degree vectopluviometers were invented and tested in the field. A vectopluviometer can rotate with the wind and align its 45-degree orifice facing the wind. Rain records at 1.5 and 9.0 meters above the ground by vectopluviometers were compared and found to differ less than 0.5% (Kurtyka et al. 1953).

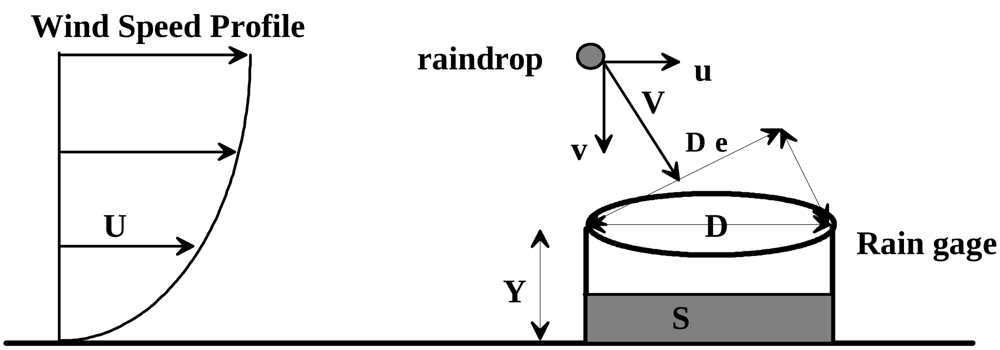

Figure 1 Orifice Opening and Rainfall Drops

In studies of wind effects on gage catch, the fall velocity of a raindrop was often assumed to be in a 45-degree diagonal direction. In fact, the fall direction of a raindrop, as illustrated in Fig. 1, depends on the raindrop velocity components as:

$$\vec{V} = u\,i + v\,j \tag{1}$$

$$\theta = \tan^{-1}\left(\frac{v}{u}\right) \tag{2}$$

where $\vec{V}$ = raindrop velocity, u = horizontal velocity component, v = vertical velocity component, and θ = angle of incidence. In the vertical direction, a raindrop develops its terminal velocity, v, when it approaches the ground as:

$$v = \left[\frac{4gd}{3C_d}\left(\frac{\rho_w}{\rho_a} - 1\right)\right]^{\frac{1}{2}} \tag{3}$$

where g = gravitational acceleration, d = diameter of raindrop, C_d= drag coefficient such as 0.67 for a 2-mm raindrop, ρ_a= density of air, and ρ_w= density of water. The terminal velocity of raindrop increases with drop size up to a plateau speed of 8.23 mps for 5-mm drop. The average size of raindrops is approximately 2 mm in diameter with a terminal velocity of approximately 6.02 mps (Chow et. al. 1988). The trajectory of a raindrop is also subject to wind effects. The prevailing direction of air flow in a turbulent boundary layer is parallel to the ground and its velocity profile can be described by

$$U = \frac{u_*}{\kappa}\ln\left(\frac{Y}{Y_o}\right) \tag{4}$$

where U = wind speed at a height Y above the ground, u_* = shear velocity, κ = von Karman's constant, and Y_o= roughness height on the ground. Re-arranging (4) with a conversion of natural logarithmic function to a base of ten yields (Guo 1999):

$$U = m \log Y + n. \tag{5}$$

where n and m = empirical parameters, depending on turbulent flow velocity profile. The advantage of such a simple model is that it takes only two measurements on the wind velocity profile to identify the values of n and m. For instance, the value of n is numerically equal to the wind speed at one foot above the ground and the sum of n and m is numerically equal to the wind speed at 10 feet above the ground. Similarly, wind speeds at one and 10 meters above the ground can be used in the metric unit system. Under the turbulent mixing process, the horizontal movement of a raindrop depends on the air flow velocity. Momentum exchange between air flow and raindrops is complicated. For simplicity, a similar concept to the vertical terminal velocity is applied to the horizontal velocity. As shown in Fig. 2, the relative motion of air flow to the raindrop can be achieved by adding a negative horizontal velocity component of the raindrop to the flow field. Under the assumption that the momentum force of the air flow on the raindrop is balanced by the horizontal drag force (Liggett 1994), the equilibrium condition of a raindrop in the horizontal direction is written as:

$$\rho_a a(U-u)^2 = C_d \frac{\rho_a u^2}{2} a \tag{6}$$

where *a* = projected area of raindrop. Re-arranging (6) yields

$$u = \frac{1}{(\sqrt{0.5C_d}+1)} U = K U \tag{7}$$

where K = horizontal velocity ratio. For instance, when C_d=0.67, the value of K is 0.63.

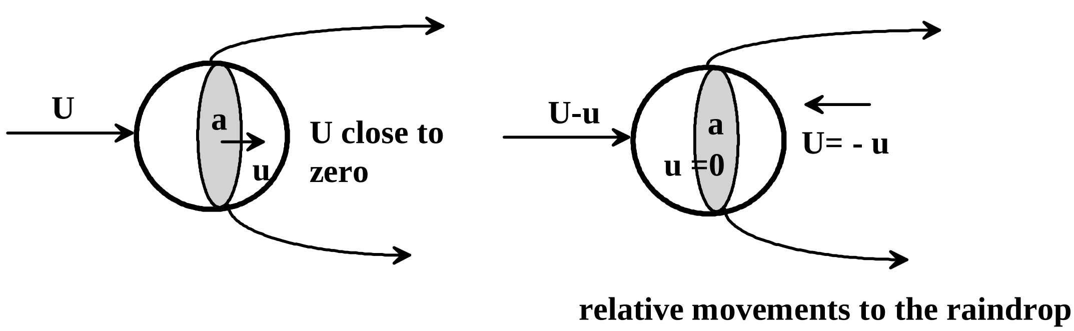

Figure 2 Drag Force around Raindrop

Aided by (1), (3), and (7), the velocity of a raindrop, $\vec{V}$, shortly above the rim of a rain gage can be estimated as:

$$\vec{V} = u\,i + v\,j = KU\,i + v\,j \tag{8}$$

The raindrop speed, V, is

$$V = \left|\vec{V}\right| = \sqrt{K^2U^2 + v^2} \tag{9}$$

The capture rate at a rain gage depends on the incoming angle of rain drops and vegetal coverage or other obstructions above the orifice opening. Different index methods have been developed to describe rain gage exposure to winds (Curtis and Burnash 1996). In this study, the effective diameter, D_e, as shown in Fig. 1, of a rain gage orifice is defined as:

$$D_e = (1-k)D\sin\theta \tag{10}$$

where k = vegetal cover factor as a reduction to the orifice diameter due to vegetal coverage or other obstructions, and D= diameter of gage orifice. A cover factor varies between zero for a clear condition and one for an entire coverage. As a result, the effective orifice area, A_e, in the direction perpendicular to the raindrop velocity is

$$A_e = \frac{\pi[(1-k)D\sin\theta]^2}{4} = A[(1-k)\sin\theta]^2 \tag{11}$$

where A = the opening area of the rain gage orifice. The captured rainfall volume, S, by the rain gage over a duration is

$$S = C\,VA_eT_d \tag{12}$$

where C = areal density of rain drops on gage orifice, and T_d = rainfall duration. Since raindrops do not form a continuous rate of flow through the orifice, the value of C reflects the intensity of the event, heavy or light. The corresponding average rainfall intensity, I, over its duration, T_d, is

$$I = \frac{S}{AT_d} = C\,V\frac{A_e}{A} = C\,V\left(\frac{D_e}{D}\right)^2 = C\,V[(1-k)\sin\theta]^2 \tag{13}$$

The value of C can be calibrated by (13) when rainfall intensity and drop velocity are measured.

UNDERCATCH OF A GAGE

When a rain gage is free from wind and vegetal coverage effects, with u = 0, k =0, and $\theta = 90^o$, (9) and (13) are reduced to

$$V_o = v \tag{14}$$

$$I_o = Cv \tag{15}$$

Considering that V_o and I_o represent the true measurements, the percentage of rain capture rate , R, at an elevated rain gage can be expressed as a ratio of (15) as:

$$R = \frac{I}{I_o} = \frac{V}{v}[(1-k)\sin\theta]^2 \tag{16}$$

By definition, the undercatch is:

$$r = 1 - R \tag{17}$$

COMPARISONS WITH FIELD DATA

Consider a situation in which the wind speed varies between 3.70 mps at one meter above the ground and 6.29 mps at 10 meters above the ground. According to (5), n = 3.70 and m = 6.29-3.70=2.59. Therefore, the wind velocity profile is described as

$$u = 2.59 \text{ Log } Y + 3.70 \tag{18}$$

The horizontal velocity ratio between the air flow and raindrop is considered as 0.63 by (7). The terminal velocity for a 2-mm rain drop is approximately 6.02 mps by (3). Under this circumstance, the rain undercatch rates at various heights are estimated by (17). As shown in Table 1, a rain gage at 3.05 meter above the ground will catch 91% of the actual rainfall amount. The experience of 14% rain capture reduction for the rain gage installed 6.10 meters above the ground is reproduced in this case. Table 1 shows good agreements between this case and Symon's data (Kurtyka et al. 1953, and Curtis and Burnash, 1996).

Vertical Distance y	Horizontal Velocity u	Total Velocity V	Incoming Angle	Effective Diameter d	Rain Capture Rate	Symons 1881 Data
ft	fps	fps	degree	ft		
Base	0.00	19.68	90.00	1.00	1.00	1.00
1.00	5.36	20.40	74.78	0.96	0.96	0.95
5.00	8.88	21.59	65.72	0.91	0.91	0.91
10.00	10.40	22.26	62.16	0.88	0.88	0.88
15.00	11.28	22.68	60.17	0.87	0.87	0.87
20.00	11.91	23.00	58.81	0.86	0.86	0.85

Table 1 Wind Effects on Rain Undercatch Rate with n=8.0 m=8.5, K=0.63, v=19.68 fps for 2 mm raindrop

Table 2 presents a comparison of two cases between the predicted and recommended undercatch rates by the National Weather Service for Automated Local Evaluation in Real Time package (ALERT). For a sensitivity test on the size of raindrops, a diameter of 2.5 mm is considered for Table 2. The terminal velocity is found to be 6.86 mps for 2.5-mm raindrops versus 6.02 mps for 2.0-mm raindrops. As shown in Table 2, the rain gage operated at 1.22 meter above the ground will experience a undercatch of 10% when the wind speed is 5.37 mps, and a undercatch of 15% for a gage operated at 3.05 meters above the ground under a wind speed of 6.71 mph. Table 3 shows the analyses of vegetal coverage effects under the same wind speed profile as used in Table 1. It indicates that the rain capture rate of a gage at 1.52 meter above the ground will reduce to 61% when the gage has a 20% vegetal coverage. In comparison, a vegetal coverage has more impact on rain undercatch than wind speed.

Wind	Horizontal	Raindrop	Incoming	Effective	Rain	Rain	ALERT
Speed	Velocity	Speed	Angle	Diameter	Capture	Undercatch	Undercatch
	u	V		De	Rate	Rate	Rate
(mps)	(mps)	(mps)	(degree)	(m)			
(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	0.00	6.86	90.00	0.30	1.00	0.00	
0.45	0.28	6.87	87.65	0.30	1.00	0.00	
2.24	1.41	7.00	78.40	0.30	0.98	0.02	
5.37	3.38	7.65	63.77	0.27	0.90	**0.10**	**0.11**
0.45	0.28	6.87	87.65	0.30	1.00	0.00	
2.24	1.41	7.00	78.40	0.30	0.98	0.02	
6.71	4.23	8.06	58.37	0.26	0.85	**0.15**	**0.15**
13.41	8.45	10.88	39.07	0.19	0.63	0.37	
22.36	14.09	15.67	25.97	0.13	0.44	0.56	

Table 2 Rain Catch under Various Wind Speeds with K=0.63, v=19.68 fps for 2 mm raindrop

Vertical	Horizontal	Total	Incoming	Cover	Effective	Rain	Rain
Distance	Velocity	Velocity	Angle	Factor	Diameter	Capture	Undercatch
y	u	V		k	d	Rate	Rate
ft	fps	fps	degree		ft		
Base	0.00	19.68	90.00	0.00	1.00	1.00	1.00
1.00	5.36	20.40	74.78	0.10	0.96	0.78	0.22
1.00	5.36	20.40	74.78	0.20	0.96	0.62	0.38
5.00	8.88	21.59	65.72	0.00	0.91	0.91	0.09
5.00	8.88	21.59	65.72	0.10	0.91	0.74	0.26
5.00	8.88	21.59	65.72	0.20	0.91	0.58	0.42
5.00	8.88	21.59	65.72	0.50	0.91	0.23	0.77
5.00	8.88	21.59	65.72	0.75	0.91	0.06	0.94
5.00	8.88	21.59	65.72	1.00	0.91	0.00	1.00
10.00	10.40	22.26	62.16	0.10	0.88	0.72	0.28
10.00	10.40	22.26	62.16	0.20	0.88	0.57	0.43

Table 3 Rain Undercatch Rate versus Cover Factor with n=8.00, m=8.50, K=0.63, and v=19.68 fps for 2 mm raindrops

In 1999, Hanson et al. reported a study conducted on the Reynolds Creek Experimental Watershed in State of Idaho, USA. This site has been established since 1987 as a part of the World Meteorological Organization's program to compare current national methods of measuring ground precipitation. The measuring systems include: (1) the Russian double-fence intercomparison reference gage (DFIR), consisting of s shielded Tretyakov gage with an orifice at 3.0 meters above the ground and two concentric wooden outer shield, (2) the Russian TRET shielded gage with an orifice at 2.0 meters above the ground, (3) the Canadian Nipher shielded snow gage (CAN) with an orifice at 1.6 meter, (4) the U.S. National Weather Service 8-in nonrecording unshielded gage (NATunshld) and shielded gage (NATshld) with an orifice at 0.94 m, (5) the Belfort universal recording gage with an unshielded orifice at 3.05 meters (BELUNSHLD), (6) the Belfort universal recording gage with an orifice at 3.05 meters and an Alter-type shield (BELshld), (7) the dual-gage (DUAL) described by Hamon in 1973, and (8) the Belfort universal recording gage with an orifice at 2.2 meters and a Wyoming shield (WYO). Since the WYO gage captured the highest rain amount during field tests, the WYO gage was chosen as a basis for determining the rain capture rate at other gages. Empirical formulas was then established between rain capture rate and wind speed as:

$$R = \alpha - \beta V \tag{19}$$

in which α and β are empirical coefficients for each type of rain gage. The values of α and β were separately developed for each rain gage tested in the Reynolds Creek Experimental Watershed study using the records collected from 1987 to 1994 (Hanson et al., 1999). Because Eq 19 does not consider the size of raindrop, the diameter of 2.5-mm was chosen for comparison. In fact, the terminal velocity is not sensitive to raindrop size. For instance, the terminal velocity of 6.02 mps is for 2-mm raindrops and 7.0 mps is the maximum value for raindrops with a diameter greater than 3-mm in diameter. The terminal velocity of 6.85 mps is used for 2.5-mm raindrops in this study. Figure 3 shows that although each gage has various shield effects, Eq 16 generally agrees with the empirical formulas, Eq 19, developed for DFIR, CAN, BELunshld, DUAL, and NATunshld gages. Eq 16 tends to overestimate the rain capture rate by 5.% for TRET and BELshld, and to underestimate the performance of NATshld gage whose rain capture rate is almost independent of wind speed.

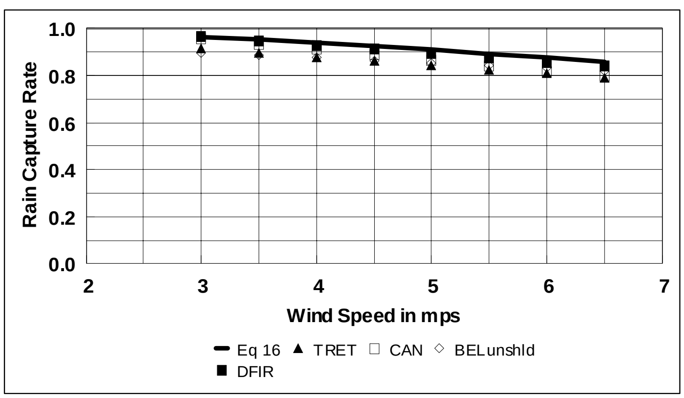

Figure 3 Comparisons with Field Data

CONCLUSIONS

Vertical variations of wind speed result in various rain capture rates. To quantify the height effect, the logarithmic velocity distribution can be described by (5). The predicted undercatch rates by (16) and (17) well match with Symmons' data. As shown in the case study, undercatch rates range from 10 to 15 % for a gage orifice operated at 1.52 to 6.10 meters above the ground. Predictions of this model also agree with the ALERT's guidance for correcting rain undercatch under various wind speeds. For instance, rain undercatch ranges from 10 to 15% under 6.71 mps or 15 mph wind and can increase to 56% under 22.36 mps or 50 mph wind. The method developed in this study was also evaluated by the empirical rain capture formulas developed for various types of rain gage in the Reynolds Creek Experimental Watershed study. Under wind speeds of 4.48 m/s and 6.70 m/s, good predictions can be achieved for

DFIR, CAN, NATunshld, BELshld, BELunshld and DUAL gages. The method developed in this study tends to overestimate the rain capture rate by 5.0% for TRET gage.

In addition to the influence of wind, vegetal coverage or other obstruction effects can also be incorporated into this model. In comparison, the coverage effects result in higher rain undercatch than wind speed. The method presented in this paper might not detect the true rainfall amount, but helps reconstruct the consistency among rainfall data. After having identified the wind speed and coverage condition during the storm event, reconstruction of rainfall data can be consistently and systematically derived from the raw data using this model. In fact, this procedure can be incorporated into the rainfall data automation process for a flash flood warming system.

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