Regular paper
Journal of the KIECS. pp. 153-160, vol. 15, no. 1, Feb. 29. 2020, t. 99, pISSN 1975-8170 | eISSN 2288-2189
http://dx.doi.org/10.13067/JKIECS.2020.15.1.153

우적 크기 탐지기 신호로 산출한 정량적 운동에너지

마르시아 모라에스* · 엘사 삼파이오** · 히까르도 테노리오*** · 윤홍주**** · 권병혁*****

Quantitative Kinetic Energy Estimated from Disdrometer Signal

M. C. da S. Moraes* · E. Sampaio** · R. S. Tenório*** · Hong-Joo Yoon**** · Byung-Hyuk Kwon*****

요 약

Brazil Alagoas 주의 동부 지역에서 우적 크기를 측정하는 디즈드로미터(disdrometer)로 산출한 강우량과 강우율의 관계로 우적의 역학 에너지가 예측되었다. 강우의 시작과 끝에서 측정되는 약한 강우 강도에서는 지수 형태의 방정식이 큰 우적의 영향을 억제하였다. 빗방울의 역학 에너지는 거의 모든 강우 강도 범위에서 과소평가 되었다. 결정 계수, 평균 절대 오차, 상대 오차 비율, 평균 절대 오차, 평균 제곱 오차, Willmott의 일치 지수 및 신뢰 지수와 같은 성과 지표에 기반을 두어 예측된 강우 역학 에너지가 유용한 결과로 평가되었다.

ABSTRACT

The kinetic energy of the rain drops was predicted in a relation between the rain rate and rain quantity, derived directly from the rain drop size distribution (DSD), which had been measured by a disdrometer located in the eastern state of Alagoas-Brazil. The equation in the form of exponential form suppressed the effects of large drops at low rainfall intensity observed at the beginning and end of the rainfall. The kinetic energy of the raindrop was underestimated in almost rain intensity ranges and was considered acceptable by the performance indicators such as coefficient of determination, average absolute error, percent relative error, mean absolute error, root mean square error, Willmott's concordance index and confidence index.

키워드

Kinetic Energy, Disdrometer, Drop Size Distribution, Erosion, Maritime Rainfall
역학 에너지, 디즈드로미터, 우적 분포, 침식, 해양성 강우

* CAPES/UFAL-Pró-Alertas Project (marciamoraes.m@gmail.com)
** Geosciences Department, University of Évora (ems@uevora.pt)
*** SIRMAL/Institute of Atmospheric Science, UFAL (tenorio_ricardo@hotmail.com)
**** 부경대학교 공간정보시스템공학과 (yoonhj@pknu.ac.kr)
***** 교신저자 : 부경대학교 환경대기과학과

· 접 수 일 : 2019. 12. 13
· 수정완료일 : 2020. 01. 14
· 게재확정일 : 2020. 02. 15

· Received : Dec. 13, 2019, Revised : Jan. 14, 2020, Accepted : Feb. 15, 2020
· Corresponding Author : Dept. of environmental atmospheric sciences, Pukyong National University,
Email : bhkwon@pknu.ac.kr

Ⅰ. Introduction

The intensity information of precipitation is of paramount importance, especially intense rainfall, since both urban and rural areas lead to major disturbances[1]. These disorders are responsible for destruction of property and human losses, mainly due to flooding, erosion and landslides. This problem was ratified through the municipal plan for risk reduction prepared for the city of Maceió[1], and more recently, the national center for risk management, prepared a document entitled physical and environmental factors of vulnerability to floods and landslides in the municipality of Maceió[2]. These technical reports are planning tools for the preparation of the diagnosis of natural disasters risk for the area of this town. Maceió´s metropolitan area has undergone a rapid and disorderly growth of the slopes of its trays, leading to an increasing number of natural disasters, sometimes with fatal victims. The Plano Municipal de Redução de Risco (PMRR) identified 572 risk sectors, whose main destructive processes were erosion, landslides and overlaps, all caused by excessive rainfall or extreme rainfall. An important erosive agent, according to CENAD, is the lack of surface drainage because there is evidence of intense surface flow on the slopes on days of heavy rains. For Imerson, the factors that influence soil erosion are the energy and amount of rain, the amount of soil covered and protected by vegetation, the characteristics of the slopes, and soil management practices[3]. So, we can understand the loss of the amount of soil during a precipitation event, especially when extreme rainfall occurs, it is necessary to analyse and to understand the impact that the kinetic energy of the drop causes in the soil.

This study unprecedented for the region by its methodology, proposes the determination of mathematical expressions capable of estimating the kinetic energy quantity of raindrops (E_{RA}), respectively, from rainfall intensity values of marine and continental origin.

Ⅱ. Materials and Methods

2.1 Experimental site and instrumentation

The State of Alagoas is in the eastern northeast region of Brazil, covering an area of 27.768 km^2[2], and is located between the parallels (08°48′12″ and 10°29′12″) of south latitude and between meridians (35°09′36″ and 38°13′54″) longitude west of Greenwich[4]. The disdrometer was installed in the municipality of Passo do Camaragibe-AL, 43.6 km away from the meteorological radar of Maceió-AL, with the geographic coordinates: latitude 09°13′15.6″ south, longitude 35°28′59.3″ west. altitude 11 m. The JWD RD-69 is an instrument that continuously and automatically (1 min) continuously measures droplet numbers in various diameters, allowing the size distribution of droplets, in Moraes this equipment is shown in greater detail[5]. Hinkle et al. suggest a correction in the kinetic energy of the drop when it is under influence of the altitude[6]. The increase in altitude causes changes in temperature and air pressure, which can bring changes in the terminal velocity of gout. Due to the altitude where the Joss-Waldvogel disdrometer (JWD), model RD69 was installed, it did not undergo an increase correction in the kinetic energy of the drop. The JWD measurements were performed within 1 minute. This equipment captures rainfall information such as speed and volume/size of the droplets. The information found in this research mainly used the droplet size distribution (DSD) and it is possible to evaluate in more detail the erosive potential of rainfall[7].

1) http://www1.folha.uol.com.br/folha/cotidiano/ult95u95887.shtml
2) https://cidades.ibge.gov.br/brasil/al/maceio/panorama

2.2 Kinetic energy of rainfall

Kinnell shows that the kinetic energy of rain can be expressed as quantity, units of energy per unit area per unit of rain depth[8]. Equation 1 represents the two parameters of kinetic energy related to each other, where E_{RR} represents the energy rate and E_{RA} the amount of energy from the rain. R is rain intensity (depth/time), c is a constant that adjusts for the differences that exist in time units.

$$E_{RA} = cE_{RR}R^{-1} \quad (1)$$

Thus, E_{RA} is expressed in $Jm^{-2}mm^{-1}$ and E_{RR} is expressed in $Jm^{-2}h^{-1}$, the c is equal to 1, if the E_{RR} is expressed in $Jm^{-2}s^{-1}$, c is equal to 1/3600.

Wischmeier and Smith determined a linear-logarithmic function for the relation, from data of drop size distribution and terminal velocity at the city of Washington DC[9]. Kinnell and Rosewell they claim that there is substantial evidence to suggest that maximal mean droplet size is reached at high intensities of precipitation (generally above 70 to 100 mm h^{-1}), after which the mean size decreases and stabilizes[3,8]. Kinnell indicated a mathematical expression in exponential form to determine the amount of kinetic energy through the rain intensity[5].

$$E_{RA} = Z(1 - \rho e^{-hR}) \quad (2)$$

where E_{RA} is the amount of kinetic energy in $J(m^2mm)^{-1}$. R is the intensity of rain (mmh^{-1}). Z, ρ and h are empirical constants. Equation 2 predicts that the amount of rain energy will approach a maximum with increasing rainfall intensity. Kinnell determined the relationship for Miami, Florida in equation (3) and for Rhodesia equivalent in territory to modern Zimbabwe in equation (4)[10], Brandt generated for the Amazon region, Brazil in equation (5)[11].

$$E_{RA} = 29.31(1 - 0.281\,e^{-0.018R}) \quad (3)$$

$$E_{RA} = 29.22(1 - 0.894\,e^{-0.0477R}) \quad (4)$$

$$E_{RA} = 30(1 - 0.56\,e^{-0.0441R}) \quad (5)$$

Kinnell suggested that an equation in exponential form, equation (6), is the one that best describes the relationship between rainfall intensity and amount of rainfall kinetic energy in $J(m^2mm)^{-1}$[8].

$$E_{RA} = E_{RA(\max)}(1 - a\,e^{-bR}) \quad (6)$$

where $E_{RA(max)}$ is the amount of the maximum energy kinetics, a and b are empirical constants. For Kinnell the coefficient a in conjunction with $E_{RA(max)}$ determines minimum amount of energy when there is rain with low or very low intensity of rain, on the other hand determines a maximum value of energy when the rain reaches great intensity of rain[8]. The coefficient b in mmh^{-1} defines the general shape of the curve. A low value of b will result in a curve that gradually approaches $E_{RA(max)}$ at high precipitation intensities.

2.3 Performance indicators

In order to provide an objective assessment of the proximity of the measurements estimated by the equation and observed by the disdrometer, were applied in this study performance indicators: determination coefficient (r^2), average absolute error (E_{abs}), percent relative error E_{rel} *(%)*), average absolute error (EAM), root mean square error (RMSE), Willmott's concordance index (d) and confidence index (c).

$$E_{abs} = E_i - O_i \quad (7)$$

$$E_{rel}(\%) = \frac{E_{abs}}{O_i}100 \quad (8)$$

$$EAM = \frac{\sum_{i=1}^{n} |E_i - O_i|}{n} \quad (9)$$

$$SE = \left[\frac{\sum_{i}^{n}(E_i - O_i)^2}{n} \right]^{0.5} \quad (10)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}\left(\left|(E_i - \overline{O})\right| + \left|(O_i - \overline{O})\right|\right)^2} \right] \quad (11)$$

$$c = rd \quad (12)$$

$$Wr^2 \begin{cases} |b| r^2 & para \quad b \le 1 \\ |b|^{-1} r^2 & para \quad b > 1 \end{cases} \quad (13)$$

where O_i is observed value, E_i estimated or approximate value, n number of observations, $\bar{O}$ mean of observed values and r correlation coefficient. The coefficient r^2 is an indicator of non-dimensional determination between the estimates and observed values. Krause et al. advise not to make an isolated evaluation of the coefficient r^2, but to combine the coefficient of angulation b of the regression line where r^2 was determined[10]. The two parameters (r^2 and b) provide a weighted version (Wr^2) of r^2. Such weighting can be performed using equation (13). Legates and Jr. suggest to quantify the error in the same unit of the variable. In this case, the rate and amount of kinetic energy are expressed in $J(m^2h)^{-1}$ and $J(m^2mm)^{-1}$, respectively[11].

The EAM and RMSE indicators are error measures used to represent the mean differences between the kinetic energy values estimated by the models and observed by the disdrometer. The RMSE provides information regarding the dispersion of the data. For small EAM, the actual data closely follow the predictions of the dependent variable, and the equation that will make the estimate of E_{RA} or will be more accurate. The Willmott concordance index (d) measures the degree to which estimated data approaches the observed data. This index ranges from zero to one, being zero, no agreement and one, perfect agreement. The index of confidence or performance (c) indicates the performance of the methods, is represented by the product of the precision index (r) and the accuracy (d).

III. RESULTS AND DISCUSSION

With the methodology suggested in equation (6) the kinetic energy quantity is determined as exponential form. The equation (14) was originated from the continental type rainfall, and has the following form in $J(m^2h)^{-1}$.

$$E_{RA} = 24.5(1 - 0.66\, e^{-0.047R}) \quad (14)$$

In equation (14) it is possible to estimate the approximate values of the amount of kinetic energy (E_{RA}*). The coefficients a and b were determined by least squares method regression. Several tests were done to select the $E_{RA(max)}$ (not described in this article). For continental type rainfall, the value of $E_{RA(max)}$=24.5 was the best fit to the parameters a and b, translating the best estimate for the calculation of the kinetic energy of the continental type rain drop.

With equation (15) it is possible to estimate the amount of kinetic energy (E_{RA}*) of the marine rainfall in $J(m^2mm)^{-1}$.

$$E_{RA} = 20.26(1 - 0.80\, e^{-0.078R}) \quad (15)$$

The $E_{RA(max)}$ represents the amount of average energy of the rains with intensity R ≥ 30 mmh^{-1}, referring to a subsample of 791 min of rainfall. Other $E_{RA(max)}$ (not described in this article) were tested, however the value of 20.26 was the best adjusted to the parameter a and b, translating a better estimate. The amount of energy determined by equation (14) and (15) suppresses the effect of the drop sample which produces low intensity but with high amounts of energy. Normally these samples are observed at the beginning and end of the rains.

Table 1 and Table 2 characterize continental and marine rainfall. These tables present information on the maximum, average and minimum intensities of rainfall, as well as maximum diameter and total number of drops per rain intensity range. We can find a direct relation between the increase in average rainfall intensity with increasing mean number of drops, with mean maximum diameter and the rate and amount of kinetic energy (observed and estimated), we calculated the mean absolute errors, percentage relative error, mean absolute error and square root mean error per class. In this way, it is possible to verify how the exponential equation $E_{RA}*$ of the marine and continental rains for each rain intensity range.

Evaluating the amount of kinetic energy through equations (14) and (15) we note that these equations normalize the kinetic energy in all classes of rain intensity. The minimum amount of rain causes the equation to calculate the least amount of energy. And for maximum rainfall intensity causes the equation to reach the maximum amount of energy. This normalization ends by suppressing the effect of the small number of low intensity samples of rainfall with high amounts of energy, usually observed at the beginning and end of the rainfall. The E_{abs} showed little variation between classes 1 and 13 (marine rainfall) and between classes 1 and 14 (continental rainfall), however in the highest rainfall intensity absolute error was too small for two types of rains.

The percentage relative error represents this difference with 0.58% (marine rainfall) and 0.74% (continental). The EAM and RMSE presented little variation with increasing rain intensity, but in the highest class of rainfall intensity these evaluation indices presented the lowest errors for both types of rain (marine and continental).

Table 1. Relative error of the power and exponential equation analysis in different classes of rain intensity (R) to determine the approximate value of the kinetic energy quantity for the continental type rainfall.

R Class	N° DSDs	$\overline{R}_{min}$ (mmh^{-1})	$\overline{R}_{max}$ (mmh^{-1})	$\overline{R}$ (mmh^{-1})	N°gt (total)	$\overline{D}_{max}$ (mm)	$\overline{E}_{RA}$ (mmh^{-1})	$\overline{E}^{*}_{RA}$ (mmh^{-1})	$\overline{E}_{abs}$ (mmh^{-1})	$\overline{E}_{rel}$ (%)	EAM	RMSE
Class 1	91	0.18	0.27	0.22	3890	1.588	10.070	8.474	−1.596	−9.62	2.431	2.990
Class 2	92	0.27	0.34	0.30	4113	1.706	11.263	8.535	−2.728	−20.3	2.948	3.732
Class 3	88	0.34	0.44	0.39	4522	1.760	12.301	8.601	−3.7	−24.44	4.007	5.289
Class 4	93	0.44	0.56	0.49	5599	1.920	13.051	8.675	−4.376	−28.41	4.557	5.927
Class 5	91	0.56	0.73	0.64	6177	1.951	13.910	8.793	−5.117	−33.25	5.210	6.240
Class 6	93	0.73	0.90	0.81	8157	1.981	13.332	8.916	−4.416	−29.59	4.551	5.276
Class 7	90	0.90	1.10	0.99	9442	2.066	14.038	9.045	−4.993	−30.13	5.254	6.571
Class 8	88	1.10	1.39	1.89	13855	2.203	15.198	9.688	−5.51	−32.57	5.665	6.453
Class 9	90	1.39	1.78	1.57	11715	2.154	15.090	9.459	−5.631	−34.35	5.717	6.379
Class 10	92	1.78	2.45	2.09	16039	2.201	15.121	9.821	−5.30	−30.89	5.469	6.377
Class 11	91	2.45	3.35	2.81	20431	2.212	15.321	11.346	−3.975	−22.89	4.253	4.923
Class 12	92	3.35	4.37	3.90	26515	2.235	15.174	11.021	−4.153	−24.53	4.291	5.045
Class 13	91	4.37	5.45	4.87	31938	2.217	15.267	11.621	−3.646	−20.65	4.021	4.669
Class 14	91	5.45	8.14	6.52	40062	2.267	15.513	12.572	−2.941	−15.74	3.331	4.303
Class 15	92	8.14	71.06	24.24	80814	2.470	17.888	17.815	−0.073	−0.74	1.631	2.038

Table 2. Relative error of the power and exponential equation analysis in different classes of rain intensity (R) to determine the approximate value of the kinetic energy quantity for the maritime type rainfall.

R Class	N° DSDs	$\overline{R}_{min}$ (mmh^{-1})	$\overline{R}_{max}$ (mmh^{-1})	$\overline{R}$ (mmh^{-1})	N°gt (total)	$\overline{D}_{max}$ (mm)	$\overline{E}_{RA}$ (mmh^{-1})	$\overline{E}^{*}_{RA}$ (mmh^{-1})	$\overline{E}_{abs}$ (mmh^{-1})	$\overline{E}_{rel}$ (%)	EAM	RMSE
Class 1	1281	0.20	0.28	0.238	100517	1.320	7.999	4.351	-3.648	-32.34	3.789	5.772
Class 2	1395	0.28	0.40	0.337	136761	1.427	8.753	4.473	-4.28	-36.29	4.387	6.484
Class 3	1252	0.40	0.54	0.467	153873	1.489	9.086	4.633	-4.453	-38.26	4.509	6.488
Class 4	1383	0.54	0.74	0.636	219733	1.509	9.138	4.837	-4.301	-37.52	4.355	6.130
Class 5	1325	0.74	0.99	0.862	250749	1.605	7.725	5.107	-2.618	-8.92	4.835	6.783
Class 6	1365	0.99	1.30	1.132	317389	1.677	10.208	5.422	-4.786	-37.71	4.834	6.846
Class 7	1309	1.30	1.68	1.482	370238	1.733	10.595	5.822	-4.773	-36.07	4.847	6.780
Class 8	1323	1.68	2.20	1.929	431546	1.790	10.943	6.315	-4.628	-34.89	4.678	6.212
Class 9	1331	2.20	2.90	2.542	500179	1.879	11.654	6.966	-4.688	-32.70	4.739	6.570
Class 10	1337	2.90	3.79	3.314	601188	1.931	12.002	7.742	-4.26	-28.32	4.350	6.219
Class 11	1314	3.79	5.18	4.454	678437	2.003	12.513	8.804	-3.709	-23.92	3.830	5.499
Class 12	1358	5.18	7.46	6.211	840048	2.092	13.323	10.262	-3.061	-16.86	3.386	5.359
Class 13	1339	7.46	11.22	9.208	993668	2.220	14.616	12.297	-2.319	-10.47	3.000	4.975
Class 14	1342	11.23	19.19	14.620	1171506	2.338	15.914	15.000	-0.914	-2.35	2.306	3.599
Class 15	1335	19.20	73.47	30.254	1439326	2.543	18.933	18.348	-0.585	-1.40	1.767	2.740

IV. CONCLUSIONS

The prediction of the kinetic energy of rain was the main objective of this research. in a form of the quantity (unit of energy per unit area per unit of rainfall), derived directly from DSDs

The equation in the exponential form, shows a normality in the amount of energy estimated by the exponential equation in several rain intensity range. If the amount of kinetic energy is the ratio between the rate of kinetic energy and the intensities of rain, then it can be said that when large droplets are found at low rainfall intensities. They generate high kinetic energy rate values leads to a high amount of energy close to or greater than the energy rate. This behavior is observed at the beginning or end of rainfall. The normality of the exponential equation suppresses the effects of large drops in low rainfall intensity and high amount of energy.

The performance indicators confirm that the coefficients found for each type of rainfall are considered acceptable. The performance indicators for exponential equation also underestimate the values observed by the disdrometer. The E_{abs} presented their lowest values at the highest intensity, mainly in continental rains. The other indicators presented little variation for different rain intensities, but always the smallest values remained in the class with the highest intensity of rainfall.

Acknowledgement

This work was funded by the Korea Meteorological Administration Research and Development Program under Grant KMI2018-06310 and by the BK21 plus Project of the Graduate School of Earth Environmental Hazard System.

References

[1] Ministério das Cidades, *Plano Municipal de Redução de Risco*, Maceió-AL, vol. 1-5, 2007.

[2] CENAD, *Levantamento de dados e análise da vulnerabilidade a desastres naturais para elaboração de mapas de risco e apresentação de proposta de intervenções para prevenção de desastres no município de Maceió-AL*, Módulo II, Ministério da Integração/Centro Nacional de Gerenciamento de Riscos e Desastres, Brasília, 2014.

[3] A. C. Imeson, "Addressing soil erosion in Europe: proceedings of the SCAPE workshop in Alicante, Spain", *Land Degradation and Development*, vol. 16, no. 6, 2016, pp. 505-508.

[4] EMBRAPA, *Boletim de Pesquisa e Desenvolvimento-Climatologia do Estado de Alagoas*, ISSN 1678-0892. Recife, 2012.

[5] M. C. da S. Moraes, "Parâmetros de radar e distribuição do tamanho de gotas de chuva continental e marinha no leste do nordeste do Brasil: sua influencia na estimativa da vazão na Bacia do Rio Mundaú", Doctoral Thesis, *Universidade Federal de Campina Grande*, 2011.

[6] S. E. Hinkle, D. F. Heerman, and M. C. Blue, "Falling water drops velocities at 1570 m elevation," *Transactions of the American Society of Agricultural Engineers*, vol. 30, no. 1, 1987, pp. 94-100.

[7] M. C. Moraes, R. S. Tenorio, E. Sampaio, H. A. Barbosa, C. A. C. Santos, H. J. Yoon, and B. H. Kwon, "Kinetic Energy Rate of the Rain Drops Based on the Impact Signal Analysis," *J. of the Korea Institute of Electronic Communication Sciences*, vol. 14, no. 4, 2019, pp. 734-754.

[8] P. I. A. Kinnell, "Rainfall intensity-kinetic energy relationships for soil loss prediction," *Soil Science Society of America*, vol. 45, no. 1, 1981, pp. 153-155.

[9] W. H. Wischmeier, and D. Smith, "Rainfall energy and its relation to soil loss," *Transactions of the American Geophysical Union*, vol. 39, no. 2, 1958 pp. 285-291.

[10] P. Krause, D. P. Boyle, and F. Bäse, "Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences," *European Geosciences Union*, vol. 5, no. 1, 2005, pp. 89-97.

[11] D. R. Legates and G. J. M. Jr., "Evaluating the use of goodnessof-fit measures in hydrologic and hydroclimatic model validation," *Water Resources Research*, vol. 35, no. 1, 1989, pp. 233-241.

저자 소개

Macia C. da S. Moraes

Coordination for the Improvement of Higher Education Personnel

Federal University of Alagoas Pró-Al ertas Project

※ Field of interest : Hydrology

Elsa Sampaio

Geosciences Department,

Institute of Mediterranean Agrarian a nd Environmental Sciences in Univer sity of Évora

Development and Research in Environment, Applied Ma nagement and Space in Lusófona University of Humanit ies and Technologies

※ Field of interest : Geosciences

Ricardo S. Tenório

1984 B.S Federal University of Alag oas, Brazil

1989 M.S University of Reading, En gland

1996 Ph.D University of Toulouse I II, France

Coordinator, Weather Radar System of Alagoas State & Institute of Atmospheric Science

Professor, Dept. of Meteorology in Federal University o f Alagoas

※ Field of interest : Radar Meteorology

윤홍주(Hong-Joo Yoon)

1983년 부경대학교 해양공학과 졸업(공학사)
1985년 부경대학교 대학원 해양학과 졸업(공학석사)
1997년 프랑스 그르노블 I 대학교 대학원 위성원격탐사전공 졸업(공학박사)
2015년 공간정보 Big Data 센터장
2015년 행정공간정보화연구소 소장
2016년 한국생태공학회 회장
※ 관심분야 : 해양 원격탐사, GIS

권병혁(Byung=Hyuk Kwon)

1986년 연세대학교 천문기상학과 졸업(이학사)
1994년 Joseph Fourier 대학교 지구유체역학 전공(이학석사)
1997년 Paul Sabatier 대학교 대기과학 전공(이학박사)
2001년~2002년 브라질 Alagoas 대학교 교수
2002년~현재 부경대학교 환경대기과학과 교수
※ 관심분야 : Atmospheric sciences, Remote sensing