

Estimating surface flow based on the equation of heavy rain type LnLn

Estimativa do escoamento superficial baseado na equação de chuvas intensas do tipo LnLn

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ABSTRACT

Runoff simulation is important in modeling various hydrological processes with application in agricultural engineering. The estimate of the surface runoff by the soil water balance method, developed by the Research Group on Water Resources at the Federal University of Viçosa, Brazil, is based on the IDF equation. This work aimed to adapt the methodology for use in locations with the LnLn-type equation. The equations for estimating the maximum instantaneous rainfall intensity and other adaptations for estimating the surface runoff were presented. Based on the intense rainfall equations of Piracicaba and Andradina, located in the state of São Paulo, Brazil, considering soils with a basic infiltration rate of 10, 25 and 50 mm.h⁻¹, the values of the soil water balance method were presented. The results showed that the differences obtained are due only to errors in the estimation of rainfall intensity due to the method of adjusting the parameters of the intense rainfall equations and that the equations presented in this article allow the use of the maximum flow depth estimation method. surface water balance for sites with the LnLn type equation.

Keywords: terraces, hydrology, hydrological modeling, runoff.

RESUMO

A simulação de escoamento é importante na modelagem de vários processos hidrológicos com aplicação em engenharia agrícola. A estimativa do escoamento superficial pelo método do balanço hídrico do solo, desenvolvida pelo Grupo de Pesquisa em Recursos Hídricos da Universidade Federal de Viçosa, Brasil, é baseada na equação do IDF. Este trabalho teve como objetivo adaptar a metodologia para uso em locais com a equação do tipo LnLn. Foram apresentadas as equações para estimar a intensidade máxima instantânea de chuva e outras adaptações para estimar o escoamento superficial. Com base nas equações de chuvas intensas de Piracicaba e Andradina, localizadas no estado de São Paulo, Brasil, considerando solos com taxa de infiltração básica de 10, 25 e 50 mm.h⁻¹, foram apresentados os valores do método de balanço hídrico do solo. Os resultados mostraram que as diferenças obtidas são devidas apenas a erros na estimativa da intensidade da chuva devido ao método de ajuste dos parâmetros das equações da chuva intensa e que as equações apresentadas neste artigo permitem a utilização do método de estimativa da lâmina máxima de escoamento superficial estimada com o método do balanço hídrico superficial para locais com a equação do tipo LnLn.

Palavras-chave: terraços, hidrologia, modelagem hidrológica, escoamento.

1 INTRODUCTION

Surface runoff estimation is important in simulating various hydrological processes, such as the generation of flood hydrographs, runoff volume estimation, building and designing a drainage system and terrace for soil conservation (Almeida et al., 2016).

The greatest difficulty in designs of safest possible structures (e.g. dams, bridges, culverts, drainage systems, terraces) lies in estimating the volume or flow resulting from surface runoff, as this depends on surface characteristics, such as soil type, degree of compaction, moisture, as well as rainfall characteristics, such as intensity and temporal distribution. Lombardi Neto et al. (1994) state that the runoff rate is the most relevant parameter for the dimensioning of gradient terraces, while for level terrace design, the runoff volume is the most important factor. Griebeler et al. (2001) point out that knowledge of the runoff volume is sufficient when the objective is to retain or store water, but when the purpose is to conduct excess water, it is more important to know the flow rate.

One of the most used methods to estimate surface runoff is the Curve Number method (CN-SCS) developed by the National Resources Conservation Service (NRCS), formerly the United States Soil Conservation Service (SCS), linked to the United States Department of Agriculture (SCS-USDA). However, Pruski et al. (2001) observed that the CN-SCS method leads to increasing values of surface runoff with the increase in the duration of the rainfall event, which is not consistent with reality.

Pruski et al. (1997) developed a method to determine the surface runoff volume in locations where the intense rainfall equation (Intensity, Duration, and Frequency – IDF) is known. This method is used in software for dimensioning terraces (Pruski et al., 1996) and calculating road drainage systems (Silva, 2011). When comparing surface runoff estimation methods, Pruski et al. (2001) concluded that the method proposed by Pruski et al. (1997) better described the decrease of surface runoff with the increase of the infiltration rate, also presenting surface runoff depths lower than those of the CN-SCS method for high soil water infiltration rates. Almeida et al. (2016) compared surface runoff estimates obtained with the CN-SCS method and with the method of Pruski et al. (1997), concluding that the CN-SCS method leads to overestimated surface runoff values

In hydrological models, runoff can be estimated based on the characteristics of intense rainfall at the site, which in turn can be described by the relationships between the quantities Intensity, Duration and Frequency, called IDF relationships. These relationships can be expressed using IDF curves or IDF equations. Griebeler et al. (2005) highlight that the IDF equations are important for the design of drainage works and erosion control structures.

Some methodologies and programs for calculating the runoff flow are based on the representative IDF equation for the site. Pruski et al. (1997) developed a methodology to determine the surface runoff volume based on the surface water balance, which is used in software for dimensioning terraces and for calculating detention basins on roads (Pruski et al., 1996; Silva, 2011). Several studies show advantages of this methodology for estimating runoff compared to other methods (Pruski et al., 1997; Pruski et al., 2001; Almeida et al., 2016).

A limitation to the use of the method developed by Pruski et al. (1997) is the dependence of the intense rainfall equations in the IDF model. Although the intense rainfall equations of the IDF model are the most used in Brazil and several other countries (Back & Cadorin, 2021), there are other intense rainfall equation models or even other methods of obtaining intense rainfall by disaggregating daily rainfall (Aragão et al., 2013; Rangel & Hartwig, 2016; Back, 2020). Back et al. (2020) adapted the runoff estimation method developed by Pruski et al. (1997) to be applied to the alternative model of the intense rainfall equation based on the disaggregation of the maximum daily rainfall.

In the State of São Paulo, it is common to use an intense rainfall equation model called LnLn type (Magni, 1984; Martinez Júnior & Magni, 1999; Martinez Júnior & Magni, 2014; Martins et al., 2017). DAEE (1982) determined the intense rainfall equations for the state of São Paulo of the LnLn type. More recently, DAEE (2018) presented the update of intense rainfall equations from 75 rainfall stations in the State of São Paulo, using equations in the LnLn model. In places where this equation model is only available, it is difficult to apply the design methods of drainage structures or programs based on the surface water balance method.

Thus, this work aimed to adapt and apply the soil water balance method to estimate surface runoff in places with the intense rainfall equations of the LnLn type.

2 MATERIAL AND METHODS

2.1 SOIL SURFACE WATER BALANCE METHOD

The methodology developed by Pruski et al. (1997) to estimate the maximum volume of surface runoff employs a soil surface water balance model, described by the equation:

$$R = P - I_a - L - E_v \quad (1)$$

where:

R = maximum surface runoff depth, mm;
P = total rainfall, mm;
I_a = initial abstractions, mm;
L = accumulated soil water infiltration, mm;
E_v = evaporation, considered null, mm.

The total rainfall, corresponding to duration t, in min, is obtained by the IDF equation

$$P = I_m \frac{t}{60} \quad (2)$$

where:

I_m = is the mean maximum precipitation intensity, mm h⁻¹, which is constant for a rainfall duration t.

To obtain I_m, the IDF equation in the form is used:

$$I_m = \frac{kT^a}{(t+b)^c} \quad (3)$$

where:

T = return period, years;
t = duration of precipitation, min; and;
k, a, b, c = location-related parameters.

Substituting equation 3 into equation 2 and deriving it in relation to time, the equation for estimating the instantaneous precipitation intensity (I_i) is obtained, as per

$$I_i = I_m \left(1 - \frac{ct}{t+b}\right) \quad (4)$$

where:

I_i = instantaneous precipitation intensity, mm h⁻¹;
t = duration of rain, min;
c and b = parameters of the IDF equation at time t;
I_m = maximum mean intensity, mm h⁻¹.

Pruski et al. (1997) demonstrated that both I_m and I_i decrease with increasing rainfall duration (t), with the maximum runoff (R) corresponding to the instant when I_i equals the soil water infiltration rate (Ti). For this condition, you can write:

$$I_m \left(1 - \frac{ct}{t+b}\right) - Ti = 0 \quad (5)$$

The value of t , corresponding to the maximum R , can be obtained using a numerical method such as the Newton-Raphson method.

From equation 5 it is concluded that for each soil condition, given by T_i , and for each hydrological condition, given by the local rainfall equation, there is a rainfall duration (t) that produces the maximum runoff (R), which is determined by equation 5.

In the water balance (equation 1), the initial abstractions (I_a) are calculated using the CN factor, using the equation recommended by the Soil Conservation Service - SCS (1972), such as:

$$I_a = 50,8 \left(\frac{100}{CN} - 1 \right) \quad (6)$$

where:

CN = number of the curve that defines the soil-vegetation hydrological complex.

As the soil water infiltration rate approaches T_i , Pruski et al. (1997) consider that the soil moisture, at the time of the project precipitation occurrence, is the maximum defined by the curve number method and the CN values are established according to the value of the basic water infiltration velocity in the soil (VIB), as shown in Table 1.

Table 1. Curve Number (CN) values and the criteria proposed by Pruski et al. (1997) for soil classification according to its basic infiltration velocity (VIB)

Soil group	Soil characteristics	VIB (mm h ⁻¹)	CN
D	Soils with high runoff potential and low infiltration speed, consisting of clayey, shallow soils with an impermeable layer	< 3	98
C	Soils with low infiltration speed when completely wet and with a barrier layer	3- 40	97
B	Soils with moderate infiltration speed when completely wet and moderately deep	40 – 190	94
A	Soils with low runoff potential, high infiltration speed when completely wet and deep profile	>190	89

Source: Griebeler et al. (2001)

The time corresponding to the occurrence of the initial abstractions is obtained through the equation:

$$T_{Ia} = \frac{I_a}{I_m} 60 \quad (7)$$

where:

T_{Ia} = time interval between the start of rain and the start of runoff, min.

The accumulated infiltration is calculated using the equation:

$$L = \frac{T_i T_{inf}}{60} \quad (8)$$

Where:

T_{inf} = duration of infiltration (min), which is obtained using:

$$T_{inf} = t - T_{la} \quad (9)$$

Once the values of P, Ia and L for the duration of precipitation obtained by equation 5 are determined, the value of R is obtained by equation 1.

2.2 INTENSE RAINFALL EQUATION OF THE LNLN TYPE

In adapting the method, the format of the equation was considered to estimate the average maximum intensity of rainfall in the LnLn model (Martinez Júnior & Magni, 1999), given by:

$$I_m = A(t + B)^C + D (t + E)^F \left[G + H \ln \left(\ln \left(\frac{T}{T-1} \right) \right) \right] \quad (10)$$

Where:

I_m = maximum mean intensity (mm min⁻¹);
T = return period (years);
t = duration of rain (minutes);

A, B, C, D, E, F, G, H, equation coefficients to be adjusted for each location.

To obtain the maximum instantaneous intensity, the equation is

$$I_i = AC(t + B)^{C-1} + DF(t + E)^{F-1} \left[G + H \ln \left(\ln \left(\frac{T}{T-1} \right) \right) \right] + I_m \quad (11)$$

Where:

I_i = maximum instantaneous intensity (mm min⁻¹);

2.3 MODEL APPLICATION

The intense rainfall equations in the LnLn model of Piracicaba, SP and Andradina (DAEE, 2018) were used, respectively, given by equations 12 and 13:

$$I_m = 44,52(t + 30)^{-0,8972} + 23,53 (t + 40)^{-0,9506} \left[-0,4847 - 0,6062 \ln \left(\ln \left(\frac{T}{T-1} \right) \right) \right] \quad (12)$$

$$I_m = 34,57(t + 20)^{-0,8809} + 2,69 (t + 10)^{-0,6683} \left[-0,4766 - 0,8977 \ln \left(\ln \left(\frac{T}{T-1} \right) \right) \right] \quad (13)$$

where:

I_m = maximum mean intensity (mm min⁻¹);

T = return period (years);
t = duration of rain (minutes);

To compare the method, the IDF equation was adjusted based on the intense rainfall estimates obtained with the LnLn equation, considering a return period of 2 to 200 years and duration of 10 to 1440 minutes, as used by DAEE (2018). The adjusted equation for Piracicaba was:

$$I_m = \frac{2787,15T^{0,211}}{(t+33,60)^{0,9169}} \quad (14)$$

And for Andradina

$$I_m = \frac{1265,46T^{0,1668}}{(t+15,53)^{0,8087}} \quad (15)$$

Where:

I_m = maximum mean intensity (mm min^{-1});
T = return period (years);
t = duration of rain (minutes).

For the application of the method, two basic infiltration rate (TIB) conditions were considered, respectively 10, 25 and 50 mm h^{-1} .

3 RESULTS AND DISCUSSION

Tables 2 and 3 show the values of the water balance parameters estimated with the two methods analyzed, respectively for Piracicaba and Andradina. It is observed that the values of initial abstractions were 1.6 mm for soils with TIB of 10 and 25 mm h^{-1} and 3.2 mm for soils with TIB of 50 mm.h^{-1} . For soils with TIB of 10 mm.h^{-1} the time for maximum runoff to occur was 144.7 min and 151.4 min, respectively, for the equations of the Piracicaba IDF and LnLn models (Table 2). For soils with TIB of 50 mm.h^{-1} , the time for maximum runoff to occur was 44.3 min and 37.2 min, respectively for the equations of the IDF and LnLn models. The runoff estimated with the IDF equation was 29.6 mm, 44.7 mm and 68.7 mm respectively for soils with TIB of 50, 25 and 10 mm.h^{-1} . With the LnLn equation, the surface runoff depths were 26.5 mm, 48.3 mm and 71.2 mm respectively for soils with TIB of 50, 25 and 10 mm.h^{-1} . For soils with a TIB of 50 mm h^{-1} , the difference between the two methods is approximately 10%, while for soils with a TIB of 10 mm h^{-1} the difference between the runoff sheets estimated with the IDF and LnLn equations is 3.6%. With the data from Andradina's intense rainfall

equations (Table 3), differences of approximately 6% were obtained. These small differences found are due to differences in the estimates of the average maximum intensities by both equations, which are results of the method of parameter adjustment

Table 2. Results of the surface water balance calculated with the intensity-duration-frequency equation - IDF and with the intense rainfall equation type LnLn for Piracicaba, SP

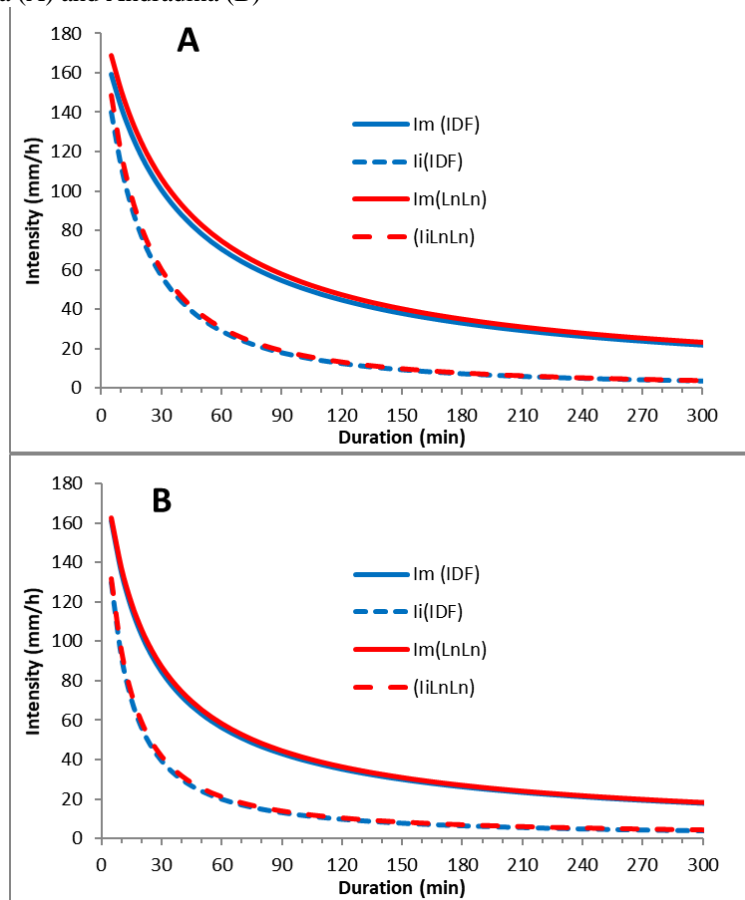
Parameter	IDF equation			Ln Ln equation		
	50	25	10	50	25	10
Infiltration rate (mm h⁻¹)						
T – Duration of rainfall to reach maximum runoff (min)	44.3	68.7	144.7	37.2	72.2	151.4
I _m – Average maximum intensity (E (mm.h ⁻¹))	83.6	65.1	39.1	96.6	66.8	40.0
P – height of rain (mm)	61.7	74.5	91.3	59.8	80.3	100.9
CN –Curve number	94.0	97.0	97.0	94.0	97.0	97.0
I _a – initial abstractions (mm)	3.2	1.6	1.6	3.2	1.6	1.6
T _{ia} – Duration of rain to reach initial abstractions (min)	1.1	0.5	0.5	1.1	0.5	0.5
L – infiltration height (mm)	28.8	28.4	24.0	30.1	29.9	25.2
R -Maximum surface runoff (mm)	29.6	44.5	68.7	26.5	48.9	71.2

Table 3. Results of the surface water balance calculated with the intensity-duration-frequency equation - IDF and with the intense rainfall equation type LnLn for Andradina, SP

Parameter	IDF equation			Ln Ln equation		
	50	25	10	50	25	10
Infiltration rate (mm h⁻¹)						
T – Duration of rainfall to reach maximum runoff (min)	23.1	48.3	119.5	24.5	50.7	122.6
I _m –Average maximum intensity (E (mm.h ⁻¹))	96.8	64.4	35.2	96.6	64.7	35.8
P – height of rain (mm)	37.2	51.9	70.0	39.5	54.7	73.1
CN –Curve number	94.0	97.0	97.0	94.0	97.0	97.0
I _a – initial abstractions (mm)	3.2	1.6	1.6	3.2	1.6	1.6
T _{ia} – Duration of rain to reach initial abstractions (min)	1.0	0.5	0.5	1.0	0.5	0.5
L – infiltration height (mm)	18.4	19.9	19.8	19.6	20.9	20.4
R -Maximum surface runoff (mm)	15.6	30.4	48.6	16.7	32.1	51.2

In Figure 1, the variation of the maximum average intensity and the instantaneous intensity of rainfall over its duration is observed, for each type of intense rainfall equation, from Piracicaba (Figure 1A) and Andradina (Figure 1B). It is evident that the maximum (I_m) and instantaneous (I_i) intensities decrease with the duration of the rain, as highlighted by Pruski et al. (1997), and that the LnLn equation reproduces the characteristics of the IDF equation in such a way that the differences in time for I_i to equal the TIB can be considered insignificant.

Fig. 1 Maximum mean intensity (I_m) and instantaneous intensity (I_i) estimated with the IDF equation and LnLn equation for Piracicaba (A) and Andradina (B)



Figures 2 and 3 show the total precipitation heights and the surface runoff estimated with the two intense rainfall equation models, respectively for Piracicaba and Andradina (Figure 3). The surface runoff layer increases until reaching a maximum point, starting to present decreasing values. The value to be used in hydrological modeling is the maximum value (LES). The values obtained with the LnLn equation are consistent with the assumptions used in the modeling and with magnitudes similar to those obtained with the IDF equation. The differences observed are due solely to errors in estimating rainfall intensity, which is a result of the method of adjusting the parameters of the respective intense rainfall equations.

Fig. 2 Total precipitation (P) and surface runoff (R) estimated with the IDF equation and LnLn equation for Piracicaba (SP) in soil with a TIB of 50 mm.h⁻¹ (A); 25 mm.h⁻¹ (B) and 10 mm.h⁻¹ (C)

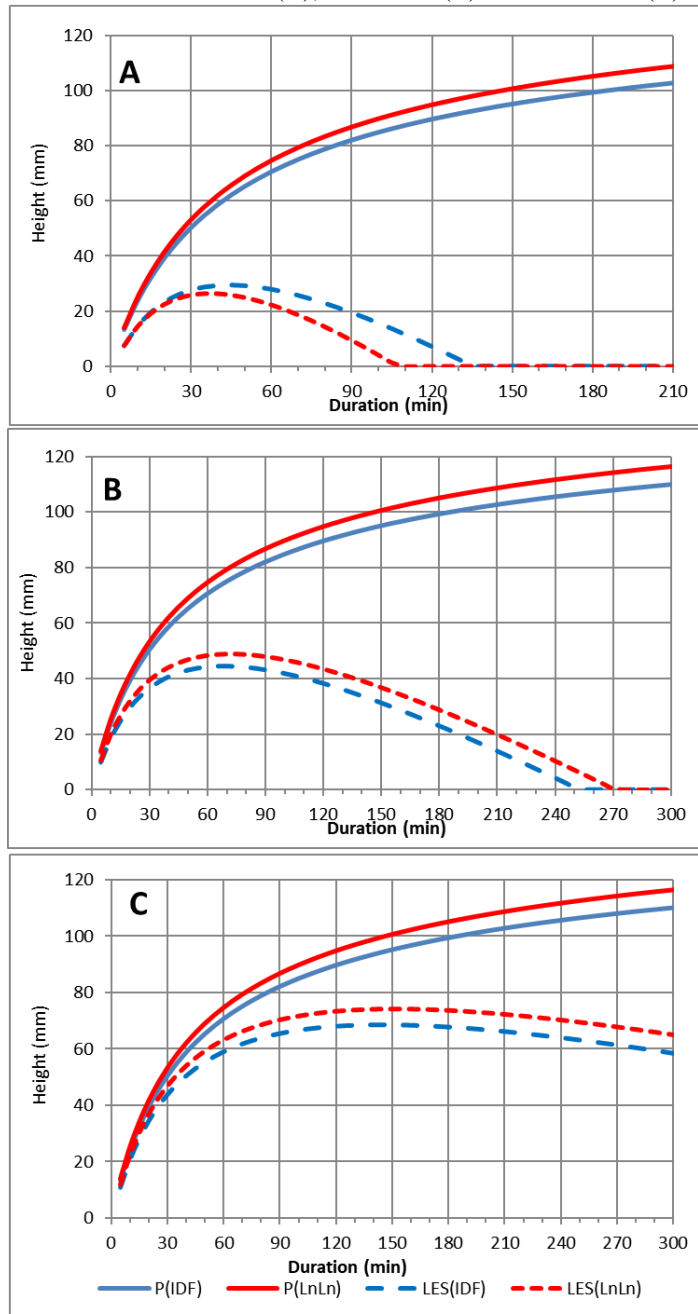
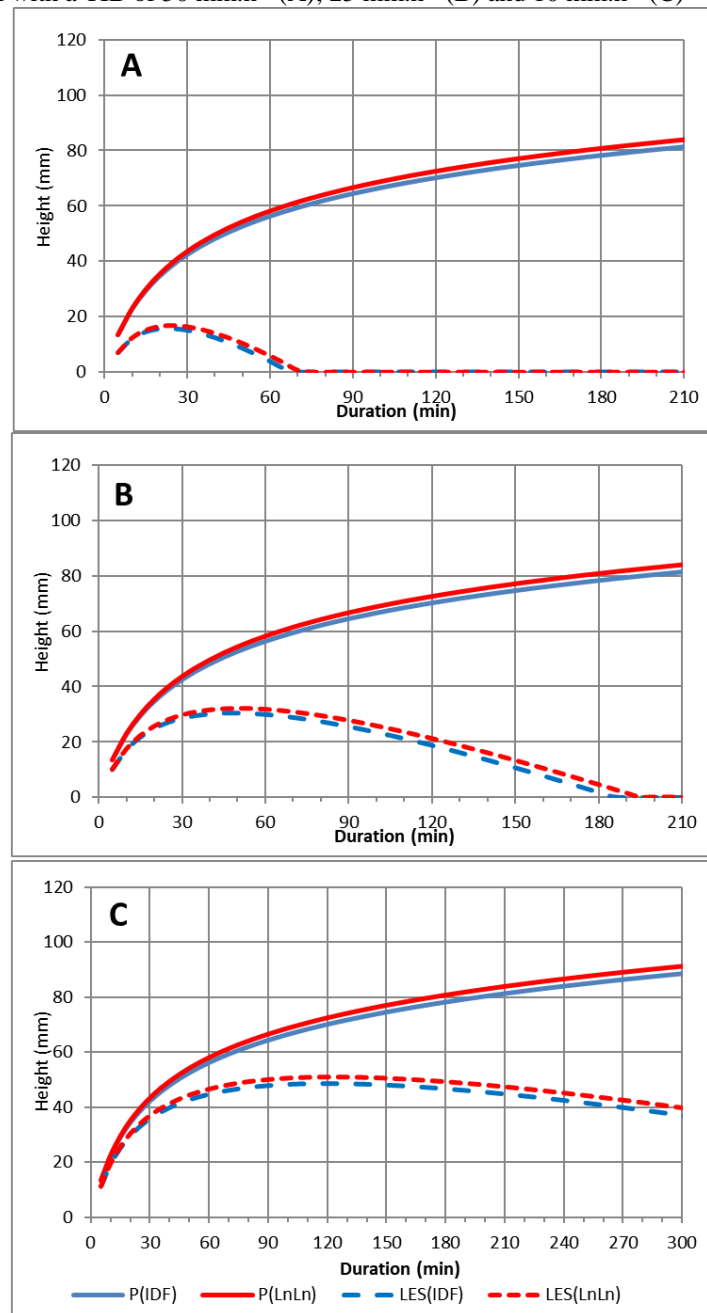


Fig. 3 Total precipitation (P) and surface runoff (R) estimated with the IDF equation and LnLn equation for Andradina (SP) in soil with a TIB of 50 mm.h⁻¹ (A); 25 mm.h⁻¹ (B) and 10 mm.h⁻¹ (C)



4 CONCLUSION

The equations presented in this article allow the use of the maximum surface runoff estimation method based on the surface water balance, for the places where the intense rainfall equations of the LnLn model are available.

This adaptation presented here allows expanding the possibilities of applying the methodology for estimating surface runoff, with the advantages of the facility of updating information on the intensity of local rain and also of the precision in estimating intense rain.

REFERENCES

ALMEIDA, R. A.; ROSA, D. R. Q.; FERREIRA, R. G. Comparação entre diversas metodologias para a estimativa do escoamento superficial em uma pequena bacia hidrográfica. *Revista Científica Vozes dos Vales*, n.10, pp.1-20, 2016.

ARAGÃO, R.; SANTANA, G. R.; COSTA, C. E. F. F.; CRUZ, M. A. S.; FIGUEIREDO, E. E.; SRINIVASAN, V. Chuvas intensas para o Estado de Sergipe com base em dados desagregados de chuva diária. *Revista Brasileira de Engenharia Agrícola e Ambiental*, v.17, n.3, Pp.243-252, 2013. <http://dx.doi.org/10.1590/S1415-43662013000300001H>.

BACK, Á. J.; CADORIN, S. B. Heavy rain equations for Brazil. *International Journal of Development Research*, v.11, pp.43332 - 43337, 2021.

BACK, Á. J. Alternative model of intense rainfall equation obtained from daily rainfall disaggregation. *Revista Brasileira de Recursos Hídrico*, v.25, e.2, 2020; <https://doi.org/10.1590/2318-0331.252020190031>.

BACK, Á. J.; WILDNER, L. P.; DENARDIN, J. E. Surface runoff estimation based on the intense rainfall equation obtained by Disaggregating daily rainfall. *International Journal of Development Research*, v.10, n.12, p. 43070-43074., 2020

Departamento de Águas e Energia Elétrica. Centro Tecnológico de Hidráulica e Recursos Hídricos (DAEE). Precipitações intensas no Estado de São Paulo: apresentação prática das relações precipitação x duração x tempo de retorno obtidas para 11 cidades. São Paulo: DAEE/CTH, 1982. 187p.

Departamento de Águas e Energia Elétrica. Centro Tecnológico de Hidráulica e Recursos Hídricos (DAEE). Precipitações Intensas no estado de São Paulo. 2018. 270 p.

GRIEBELER, N. P.; PRUSKI, F. F.; MARTINS JÚNIOR, D.; SILVA, D. D. Avaliação de um modelo para estimativa da lâmina máxima de escoamento superficial. *Revista Brasileira de Ciência do Solo*, v.25, pp.411-417, 2001.

GRIEBELER, N. P.; PRUSKI, F. F.; SILVA, A. M. J.; RAMOS, M. M; SILVA, D. D. Modelo para a determinação do espaçamento entre desaguadouros em estradas não pavimentadas. *Revista Brasileira de Ciência do Solo*, v.29, Pp.397-405, n.3, 2005.

LOMBARDI NETO, F.; BELLINAZZI JR, R.; LEPSCH, I. F.; OLIVEIRA, J. B.; BERTOLINI, D.; GALETI, P. A.; DRUGOWICH, M. I. Terraceamento agrícola. In: LOMBARDI NETO, F.; DRUGOWICH, P.I. Manual técnico de manejo e conservação do solo e da água. Campinas: CECOR – CATI, v.4, c.3, pp.1-34. 1994.

MAGNI, N. L. G. Estudo pontual de chuvas intensas - proposição e análise de uma metodologia de estudo das relações intensidade duração frequência definidas para um ponto. 1984. Dissertação (Mestrado em Engenharia Civil) - Escola Politécnica da Universidade de São Paulo, 1984

MARTINEZ JÚNIOR, F.; MAGNI, N. L. G. Equações de chuvas intensas do Estado de São Paulo. São Paulo: DAEE; EPUSP, 1999

MARTINEZ JÚNIOR, F.; MAGNI, N. L. G.. Precipitações intensas no Estado de São Paulo. São Paulo: DAEE; CTH, 2014

MARTINS,D.; KRUK, N. S.;MAGNI, N. L.; QUEIROZ, P. I. B. Comparação de duas metodologias de obtenção ode equação de chuvas intensas para a cidade de Caragatatuba (SP). Revista DAE,P p.34-49, 2017. DOI:10.4322/dae.2016.033

PRUSKI, F. F.; GRIEBELER, N. P.; SILVA, D. D. Comparação entre dois métodos para a determinação do volume de escoamento superficial. Revista Brasileira de Ciência do Solo, v.25, Pp.403410, 2001.

PRUSKI, F. F.; FERREIRA, P. A.; RAMOS, M. M.; CECON, P. R. Model to design level terraces. Journal of Irrigation and Drainage Engineering, v.123, pp.8-12, 1997.

PRUSKI, F. F.; SILVA, J. M. A.; CALIJURI, M. L.; BHERING, E. M.. Terraços for Windows v.1.0. Dimensionamento e manejo de sistemas de conservação de solos e drenagem de superfície – Manual do usuário. Viçosa, Universidade Federal de Viçosa Departamento de Engenharia Agrícola, 1996. 38p

RANGEL, E. M.; HARTWIG, M. P. Análises das curvas de intensidade-duração-frequência para a cidade de Pelotas através de uma função de desagregação. Revista Thema, v.14, n.2, pp.63-77, 2016.

SCS. National engineering handbook. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service (SCS), 1972.

SILVA, D. P. Modelo para dimensionamento de sistemas de drenagem de superfície em estradas não pavimentadas. 2011. Tese (Pós-Graduação em Engenharia Agrícola) – Universidade Federal de Viçosa, Viçosa, 2011.