Determination of Curve Number for snowmelt-runoff floods in a small catchment

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Abstract. One of the widely used methods for predicting flood runoff depth from ungauged catchments is the curve number (CN) method, developed by Soil Conservation Service (SCS) of US Department of Agriculture. The CN parameter can be computed directly from recorded rainfall depths and direct runoff volumes in case of existing data. In presented investigations, the CN parameter has been computed for snowmelt-runoff events based on snowmelt and rainfall measurements. All required data has been gathered for a small agricultural catchment ($A = 23.4\,\mathrm{km}^2$) of Zagożdżonka river, located in Central Poland. The CN number received from 28 snowmelt-runoff events has been compared with CN computed from rainfall-runoff events for the same catchment. The CN parameter, estimated empirically varies from 64.0 to 94.8. The relation between CN and snowmelt depth was investigated in a similar procedure to relation between CN and rainfall depth.

1 Introduction

Determination of effective rainfall defined in hydrology as a portion of total rainfall that contributes to runoff is a crucial step in application of rainfall-runoff models. One of the often used approaches is the so called Curve Number (CN) method. This method was created in c. 1950 by USDA Soil Conservation Service (Hawkins et al., 2010). Since this time, the method has been applied for an estimate of effective rainfall in various catchments. In Poland, the method were applied in agricultural catchments (Banasik and Ignar, 1983; Miler, 2012) and urban catchment (Banasik and Pham, 2010) as well. The application of CN method for snowmelt conditions is rare. However, it is used in continuous modelling (Van Mullen et al., 2002). This paper presents an attempt for application of the CN method for snowmelt runoff events based on measured snow water content, rainfall and runoff in a small lowland catchment.

2 Study area and catchment

2.1 Location and size of the catchment

Hydrological field investigation in a river of Zagożdżonka was started by the present Department of Hydraulic Engineering of Warsaw University of Life Science in 1962 at Płachty Stare gauge. Some 20 years later, monitoring of the river flow at Czarna gauge has begun. Since 1991 the investigation has been intensified and the river gauging station at Czarna has been equipped with automatic recorders of rainfall water level and with devices measuring water quality parameters, i.e. temperature, turbidity and sediment transport. Later, an electronic system of data recording, logging and transmitting was installed. Zagożdżonka catchment, shown in Fig. 1 is located in central Poland, about 100 km south of Warsaw. The catchment area at Czarna is $23.4\,\mathrm{km}^2$.

2.2 Rainfall, snowmelt and runoff

The mean annual precipitation and runoff are estimated at 610 and 106 mm respectively, on the bases of 50-year (1963–2012) data records collected by the Department of Hydraulic Engineering of Warsaw University of Life Sciences
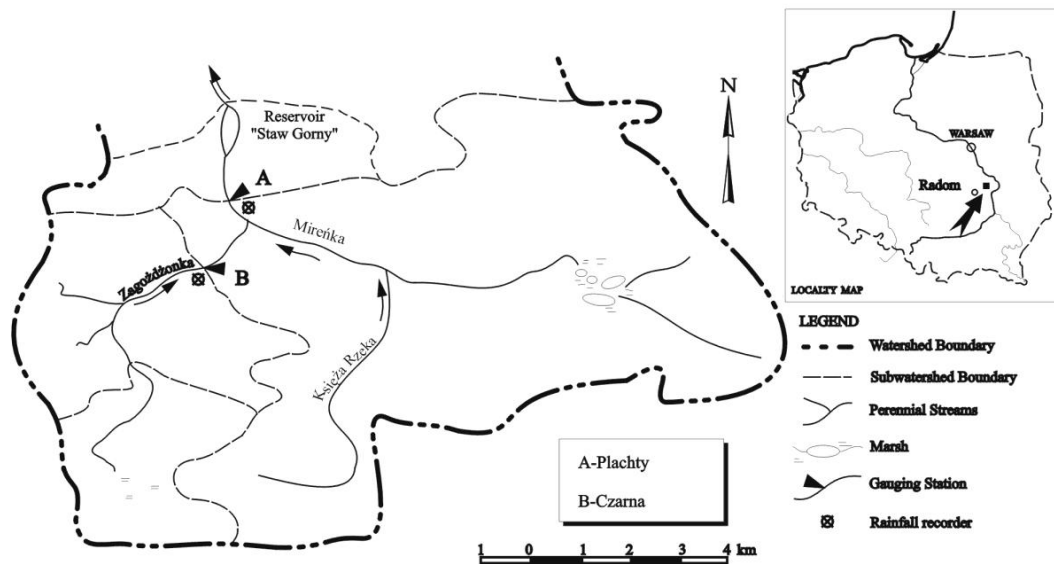
Figure 1. Locality map of the catchment.

at Płachty Stare, except for precipitation data for the period 1963–82. This period of data was taken from available publications of Polish hydro-meteorological service IMiGW for the nearest rain gauge Zwoleń. The maximum precipitation of 941 mm was recorded in 1974 and the minimum of 414 in 1991. Maximum annual runoff of 209 mm was measured in 1980 and the minimum of 52 mm in 1992. The winter period precipitation (December–February), mainly in the form of snow, is c. 103 mm, i.e 16.9 % of the annual amount (Banasik et al., 2014b). According to the thermal and snowiness classification (Hejduk and Hejduk, 2014), temperate cold and extraordinarily low snowy winters has dominated in Zagożdżonka catchment in time of 2003–2013. The decreasing number of days with thick snow was recently observed. The snow cover in Czarna usually appears at the end of November and disappears at the end of March, resulting in a total number of days with snow, equal to 67 and snowmelt periods 1–4 days long (Hejduk and Hejduk, 2014).

2.3 Topography, land use and soils

Topography of Zagożdżonka catchment is typical for lowlands in Central Poland. Absolute relief is 26.5 m in the (shown as B) in the Fig. 1. The mean slopes of main streams are from 2.5 to 3.5 m per 1000 m. Local depressions, which do not contribute to direct runoff and sediment yield from the catchment, constitute a significant part of the area 3.8 km² upstream of Czarna. Land use is dominated by arable land (small grains and potatoes), which occupies about 70 %, one fifth (20 %) being covered by forest and about 10 % for pasture (Banasik, 1994). Sandy soils are the dominant type in the watershed area (light loamy sand – 40.2 %; loamy sand 50.5 % and organic soils – 9.3 %).

3 CN determination

3.1 CN for rainfall-runoff events

The curve number is a parameter which can be estimated based on existing rainfall-runoff events as well as based on hydrological properties of soils cover conditions and land use. Using rainfall-runoff data, the empirical CN can be calculated by following the relationship of (Banasik et al., 2014a):

$$\mathrm{CN} = \frac{25\,400}{S + 254} \tag{1}$$

where CN is a dimensionless parameter varying from $(0.100>$, S – maximum potential retention of the particular catchment (mm), 25 400 and 254 are numbers arising from recalculation of original equation to metric system. The relation of direct runoff depth H (mm) and rainfall depth P (mm) is given in a set of equations:

$$H = \frac{P - 0.2S^2}{P + 0.8S} \quad \text{if} \ \ P > 2S \tag{2}$$

$$H = 0 \quad \text{if} \ \ P \le 2S \tag{3}$$

After transformation of Eq. (2) against S it is possible to calculate it based on P and H and afterwards of coefficient CN, by use of Eq. (1).

3.2 CN for snowmelt-runoff events

The Eq. (2) has been applied for snowmelt events. The main idea was to recalculate measured snow depth into an amount of water based on daily snow sampling (Hejduk and Banasik, 2011). The depth of snow, as well as weight and volume of

Table 1. Characteristics of 28 snowmelt or snowmelt rainfall events.

Category	Unit	Value for events	
		average	range
Snowmelt and Rainfall ($M + P$)	mm	28.98	5.90–69.30
Runoff depth (H)	mm	3.27	0.19–16.17
Peak discharge (Q)	m^3 s^{-1}	0.77	0.14–3.44
CN	–	79.3	64.0–94.8

Figure 2. CN vs. MP. CN$_0$ represent a threshold, below which no runoff occurs until the snowmelt MP in mm exceeds an initial abstraction of 20 % of the maximum potential retention.

the snow sample were measured using Chomicz snow sampler (Janiszewski, 1988), with daily time step. According to the sampler's construction (cross-section of the pipe), the weight of the snow sample in grams is numerically equal to snow water content in millimetres.

It was assumed that snowmelt runoff from catchment was caused by snowmelt M (mm) or the sum of snowmelt M and rainfall P (MP) in the case of mixed, snowmelt-rainfall events. This assumption leads to modification of Eq. (2) in the following way:

$$H = \frac{(M + P) - 0.2S^2}{(M + P) + 0.8S} \quad \text{if} \quad P > 2S \tag{4}$$

where M is a snowmelt depth (mm) and P is a rainfall depth (mm).

This simple modification was applied to calculate the CN factor for snowmelt-runoff and snowmelt/rainfall-runoff events.

4 CN number for snowmelt-runoff snowmelt/rainfall-runoff events with comparison to rainfall-runoff events.

Using Eqs. (1) and (4) together with daily snowmelt-runoff and snowmelt/rainfall-runoff events, the CN was estimated for 28 events measured between 1998–2012 for the Czarna gauging station. Basic characteristic of considered events are presented in Table 1.

The CNs estimated from recorded data in comparison to snowmelt MP are presented in Fig. 2. The dots representing CN and MP pairs of data indicate the relation between those values.

In case of rainfall-runoff data, (Hawkins, 1993; Hawkins et al., 2010) proposed to use an "asymptotic" approach for approximation of CNs and rainfall P relation after adoption of frequency matching technique. This method assumes, that rainfall depth and direct runoff depth are stored separately and then realigned on the rank-order basis to form $P : H$ pairs of equal return periods (Banasik et al., 2014a). A standard asymptote occurs according to formula 5 when there is a decline tendency of CN with increase of P.

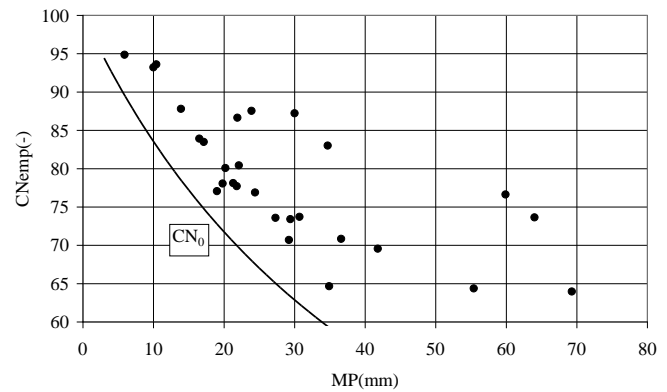$$CN(P) = CN + (100 - CN_\infty) \exp\left(\frac{-P}{b}\right) \tag{5}$$

where CN_∞ is a constant approached as $P \to \infty$; and b is a fitted constant.

The analyses conducted for Czarna station after applying matching technique for 71 rainfall and runoff data pairs resulted in Eq. (6) (Banasik et al., 2014b) that is a projection of asymptote proposed by Hawkins (1993). This form of relation was also investigated by other authors (Stewart et al., 2012; Tedela et al., 2011).

$$CN(P) = 70.6 + 29.4 \exp(-P/22.0) \tag{6}$$

where CN and P are the Curve Number and rainfall depth, 70.6 is a constant approached when $P \to \infty$ often indicated as CN_∞, 29.4 is a parameter equal 100–CN_∞ and 22.0 is a fitted parameter b.

The similar procedure was applied for investigating snowmelt-runoff events. It results in determination of new asymptote parameters for snowmelt conditions:

$$CN(MP) = 71.3 + 28.7 \exp(-MP/18.1) \tag{7}$$

with the $r^2 = 0.91$ and standard error SE $= 1.56$

where CN and MP are the Curve Number and snowfall + rainfall depth, 71.3 is a constant approached when $MP \to \infty$, and 28.7 is a parameter equal 100–CN_∞ and 18.1 is a fitted parameter b.

5 Conclusions

The CN calculated from measured snowmelt-runoff events show a large variation from 64 to 94.8 with the average value calculated as 79.3. The comparison of CN and MP suggests decreasing the relation in a similar way to decreasing the CN and rainfall relation already investigated in this catchment. The parameters of the relation proposed by Hawkins (1993) received for snowmelt-runoff events were closed to parameters received for rainfall-runoff events for the Czarna gauge. The CN_∞ in case of snowmelt-runoff were higher (71.3) in

comparison to the rainfall-runoff (70.6) and the fitted parameter was lower in case of the snowmelt-runoff events. The CN_∞ obtained for snowmelt can be assumed as an identifying CN for winter/spring periods for Czarna station in Zagożdżonka catchment. It can be applicable for a design snowmelt/snowmelt rainfall events.

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