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Flood Peak Discharge vs. Various CN and Rain Duration in a Small Catchment

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1. Introduction

Estimations of flood peak discharges of low probability of exceedance are required for designing and maintaining hydraulic and road structures (reservoirs, weirs, water intakes, bridges, culverts) as well as for flood protection, including assessment of the risk of flooding. Rainfall-runoff models are usually the only alternative for such estimations in case of small catchments as there is a lack of sufficient, good quality historic data to be used for applying the traditional i.e. statistical methods (Hlavcova et al. 2005). The aim of this study was to check responses of a small agro-forested catchment to rainfall of assumed 1% probability of exceedance and of various duration, and with various potential of the catchment to form runoff, characterize by a changeable Curve Number – CN (Ignar 1988, USDA-NRCS 2003, Miler 2012). Field data of rainfall-runoff events, recorded in the investigated catchment of Zagożdżonka river since 1980, were used to estimate the model parameters (Banasik 2011, Banasik et al. 2014).

2. Description of research area and methodology

2.1. Location and characteristics of the investigated catchment

The Zagożdżonka catchment (Fig. 1) is a small agro-forested, lowland catchment, located in central Poland, about 100 km south of Warsaw.

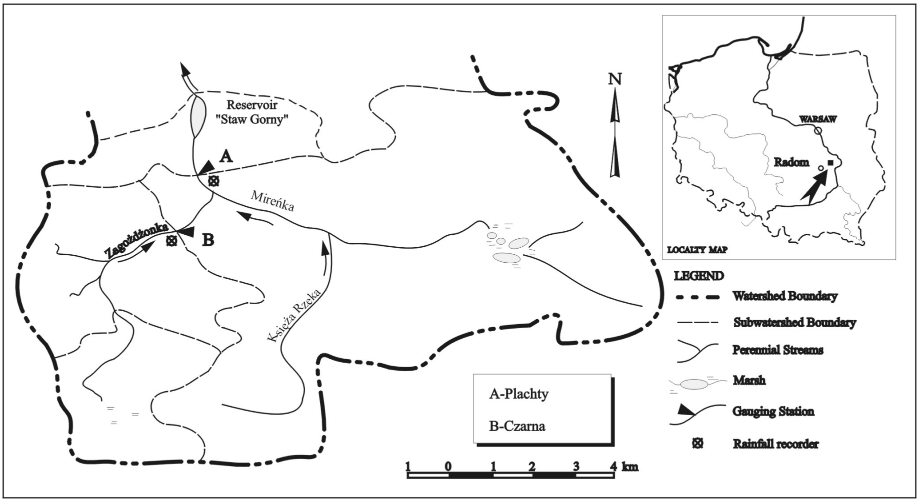

Fig. 1. Locality map of the Zagożdżonka catchment and gauging stations
Rys. 1. Mapa lokalizacyjna zlewni rzeki Zagożdżonki i profili badawczych

The Zagożdżonka River is left tributary of the Vistula River with its outlet (N:51º39'28"; E:21º29'13") near Kozienice town. Hydrological field investigations of the Zagożdżonka River, at Płachty (A on Fig. 1; N:51º26'43.8"; E:21º27'35.6"), have been carried out by the Department of Water Engineering and Environmental Restoration of Warsaw University of Life Sciences since 1962. In the first period, the river water stages have been recorded by an observer, who was reading staff gauge three times a day, except flood periods when reading was usually carried out each hour. Since 1980 monitoring of the river stages has been carried out with the use of mechanical water stage recorder, and since middle of last the decade of the previous century with the use of electronic system for recording, logging and transmitting the data. In the recent periods, the traditional reading of staff gauge has been continued for correcting the records once a day. For precise estimation of river flow, a rating curve has been established and verified at least once a year based on 10-12 hydrometric measurements The catchment area upstream of the Płachty gauging station is 82.4 km^2. Mean annual values of precipitation 612 mm, and mean runoff coefficient is 17.3%. The mean elevation of the catchment is about 163 m above sea level, and absolute relief is 37.0 m (upstream of A, Fig. 1). The mean slopes of the main channels range 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, i.e. ca 24% (Banasik & Hejduk 2012).

2.2. Description of the rainfall-runoff procedure

A procedure called SEGMO (SEdiment Graph MOdel), developed at Warsaw University of Life Sciences for analyzing rainfall-runoff events in small catchments and for predicting catchment responses to heavy rainfall (Banasik 1994, Banasik & Walling 1996) was used in the investigation. In the previous investigations, it was proved that SEGMO, based on lumped parametric approach, is useful tool for predicting flood hydrographs, as catchment response to extreme rainfalls (Banasik 2011, Karabova et al. 2012, Krajewski at al. 2014). The model consists of two parts; a hydrologic sub-model and sedimentology submodel. The hydrologic submodel uses the Soil Conservation Service CN-method to estimate effective rainfall and the instantaneous unit hydrograph (IUH) procedure to transform the effective rainfall into a direct runoff hydrograph. The sedimentology submodel uses a form of the modified Universal Soil Loss Equation (Williams 1978, Banasik & Gorski 1993) to estimate the amount of suspended sediment produced during the rainfall-runoff event and the instantaneous unit sedimentgraph (IUSG) procedure to transform the produced sediment into a sedimentgraph (Banasik et al. 2005, Banasik & Hejduk 2014). Only the first one i.e. hydrological submodel, called later rainfall-runoff model, will be used for prediction of the runoff hydrographs. Schematic representation of the model is shown in the Figure 2.

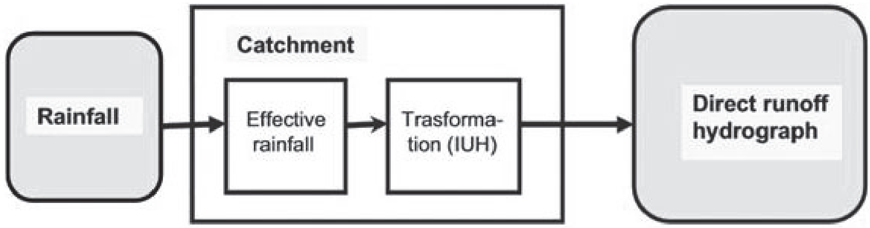

Fig. 2. Schematic representation of rainfall – runoff model
Rys. 2. Schemat blokowy modelu opad-odpływ

2.3. Input data and model parameters used for the computation

A formula of Bogdanowicz and Stachy (1998) on relationship of intensity-duration-return period, applicable also for region of center of Poland, has been used to find rainfall depths of the events with probability of exceedance of 1% (return period of 100 years) and various duration (i.e. D = 6, 12, 18, 24, 30, 36, 42, 48, 60 and 72 h), as input data for runoff hydrograph simulation. Rainfall intensity for each of the 10 events has been assumed as a constant during rain duration. The computed relationships of rainfall intensity and rainfall depth, as well as runoff depth, estimated according to curve number – CN as described below, versus rain duration are presented in Fig. 3.

Both, the curve number, which is determining runoff depth from rainfall depth, and the IUH characteristics (such as lag time, time to peak, maximum ordinate), which are used to transform the runoff depth into direct runoff hydrograph, have been estimated on the base of recorded in the catchment rainfall-runoff events (Banasik et al. 2011, Banasik et al. 2014). All of them include some stochastic variables, however IUH parameters have been approximated, and used in computation as deterministic, i.e. N (number of reservoirs) = 3.27 and k (retention parameter of each reservoir) = 3.58 hours. A big variability in CNs has been found, when they were computed from recorded rainfall-runoff data. So, using the 40 rainfall-runoff data set, the curve numbers were computed again, for each of the ordered pairs, as suggested by Hawkins (1993), and finally plotted against rainfall depth.

Curve numbers were found to approximate an exponential function, varying with storm depth in the form (Banasik et al. 2014):

$$CN(P) = 69.8 + 30.2 \cdot \exp(-P/20.1) \quad (1)$$

where:
CN(P) – curve number (–),
P – rainfall depth (mm).

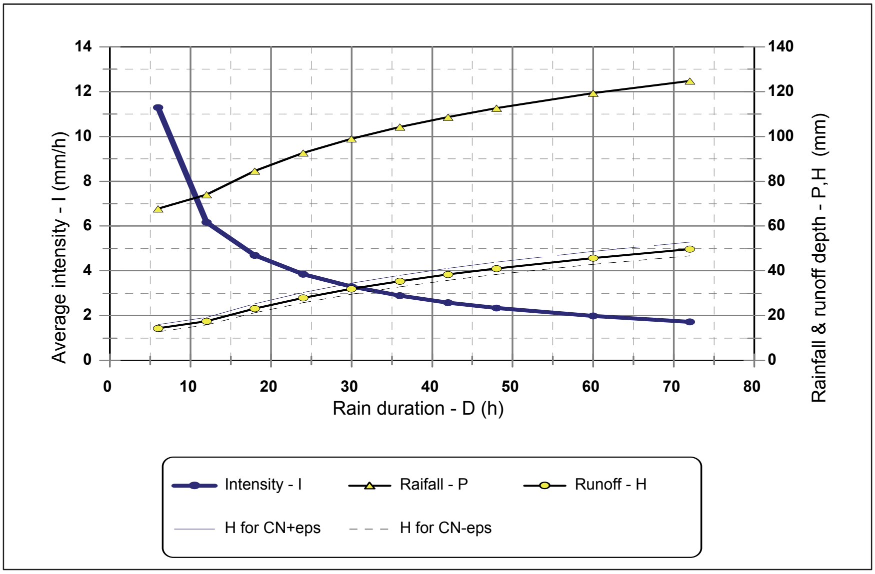

Fig. 3. Rainfall intensity-duration and depth-duration relationships of return period of 100 years for center of Poland with runoff depths for Zagożdżonka catchment

Rys. 3. Zależności natężenie-czas trwania i warstwa-czas trwania opadu o okresie powtarzalności 100 lat dla centrum Polski z warstwami odpływu ze zlewni Zagożdżonki

Standard error of estimation of CN in formula 1 was ε=1.54. CN value according to the formula 1 is decreasing with rainfall increase, what was called by Van Mullem et al. (2002) as standard behavior of a catchment, and approaches a constant value of 69.8 at higher rainfalls, which is very close to that value estimated on the base of soil type and land use, i.e. CN_{table}=71.5 (Banasik 1994).

Runoff depth for each of the 10 assumed events was computed from the USDA-NRCS (2003) formula:

$$H = \begin{cases} \dfrac{(P-0.2S)^2}{(P+0.8S)} & for \;\; P > 0.2S \\ 0 & for \;\; P \le 0.2S \end{cases} \quad (2)$$

where:
H – estimated runoff depth (mm)
S – maximum potential retention (mm), computed from the equation:

$$S = 25.4\left(\frac{1000}{CN(P)} - 10\right) \quad (3)$$

where CN(P) has been estimated according to formula 1. The computations have been then repeated for CN(P) ± ε (i.e. increasing and decreasing the value of CN of the standard error of estimation, respectively). Results of the runoff depths – H are presented in the Figure 3.

For the rainfall of return period of 100 years, the rainfall depth increases from 67.8 mm when the rain duration is 6 hours to 124.9 mm when the rain duration is 72 hours. The Curve Number according the eq. 1 would decrease from 70.8 to 69.8 for the respective rain durations and depths, and the runoff depths would increase from 14.5 mm to 49.8 mm. The variation of CN of its standard error of estimation ε = 1.54 would cause changes in runoff depth from 13.0 mm to 16.1 mm for rain duration of 6 h and from 46.8 to 52.9 for rain duration of 72 hours.

3. Results

3.1. Prediction of flood hydrographs

The responses of the Zagożdżonka catchment to each rainfall event has been computed with the use of the following assumption: constant rainfall intensity, no areal reduction of the rainfall depth, formation of runoff during the rain – according the formula 2, i.e. with initial losses equal to 20% of maximum potential retention, instantaneous unit hydrograph is unchanged and computed according to Nash model with parameters defined in the section 2.3. Time step of computation has been assumed as one hour. Predicted flood hydrographs as a response of the catchment to rainfall event of 100 year return period of various duration and for CN estimated according the eq. 1 are shown in the Figure 4. One can notice from the Fig. 4 that there is initial increase of peaks of runoff hydrographs with rain duration, with maximum of 27.3 m^3/s at D = 30 hours, and then the peaks of runoff hydrographs are decreasing. This is the effect of simultaneous increase of runoff volume and decrease of rainfall (and runoff) intensity.

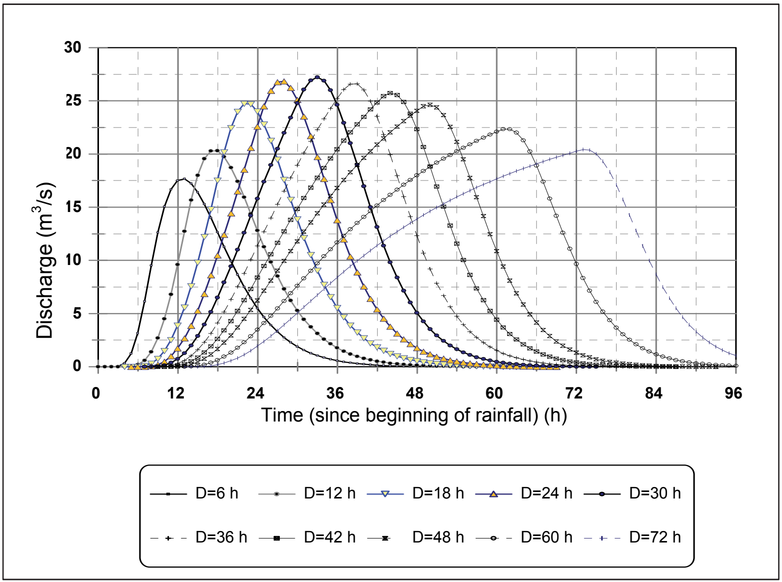

Fig. 4. Simulated direct runoff hydrographs for rainfall of return period of 100 years and for various duration (D)
Rys. 4. Hydrogramy odpływu bezpośredniego dla opadów o okresie powtarzalności 100 lat i o różnym czasie trwania (D)

3.2. Flood peak discharge vs rain duration for various Curve Number

Peaks of direct runoff hydrographs computed as responses of the analyzed catchment to rainfall events of 100 year return period, and with the CNs estimated according to eq. 1, seen in the Fig. 4, are shown in the Fig. 5, versus rain duration (as the blue line – for CN). The maximum value of peak discharges of 27.3 m^3/s was reached for rain duration of 30 hours. Taking into account the standard error of estimation of

CN in equation 1 (i.e. ε = 1.54), the maximum value of at peak discharges were also reached for duration of 30 hours, approaching 28.9 m^3/s for CN+ε and 25.5 m^3/s for CN-ε (Fig. 5). This indicates that changes of the Curve Number, i.e. increase or decrease of the standard error of estimation would change the maximum discharge of 5.6% and -6.6%, respectively.

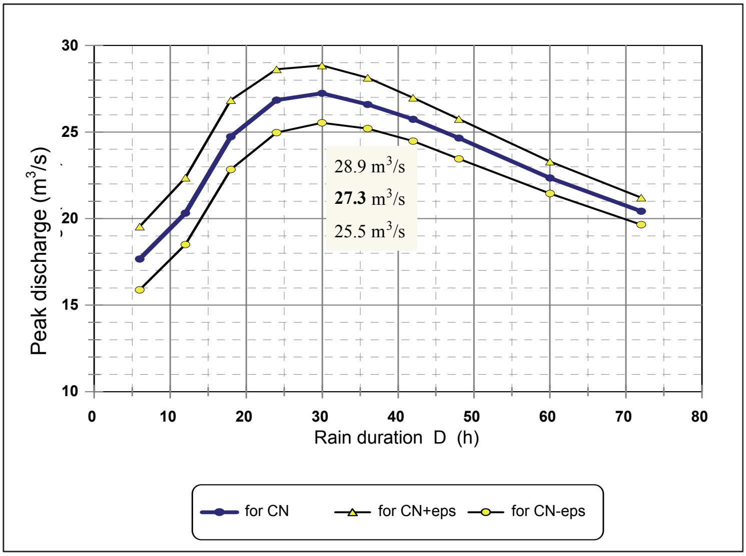

Fig. 5. Computed peaks of direct runoff hydrographs of rainfall events of 100 year return period, with various CNs, versus rainfall duration
Rys. 5. Przepływy maksymalne hydrogramów odpływu bezpośredniego, wywołanego opadami o okresie powtarzalności 100 lat, dla różnych wartości CN, w zależności od czasu trwania opadu

4. Conclusions

- The rainfall-runoff procedure indicated high sensitivity of peak discharge to CN value (change of 1.54 in CN made ca. 6% change in flood flow).
- The initial increase of peaks of runoff hydrographs with rain duration, and then the gradual decrease of the peaks is the effect of simultaneous increase of runoff volume and decrease of rainfall (and runoff) intensity.

Acknowledgment

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References

Banasik, K. (1994). *Model sedymentogramu wezbrania opadowego w malej zlewni rolniczej* [Sedimentgraph model of rainfall event in small agricultural watershed; in Polish with an English summary]. Theses & Monographs, 191. Warsaw: Warsaw Agricultural University-SGGW Press.

Banasik, K. (2011). Catchment responses to heavy rainfall events in a changing environment. In: *Prediction and reduction of diffuse pollution, solid emission and extreme flows from rural areas: case study of small agricultural catchments*, 61-74. Warsaw, WULS-SGGW Press.

Banasik, K. & Gorski, D. (1993). Evaluation of rainfall erosivity for East Poland. Proc. International Symposium on *Runoff and Sediment Yield Modelling*, Eds: Banasik, K. & Żbikowski, A. Warsaw, Poland, Sept. 14-16, 1993, Warsaw Agricultural University Press, 129-134.

Banasik, K. & Hejduk, A. (2014). Ratio of basin lag times for runoff and sediment yield processes recorded in various environment. *Sediment Dynamics from the Summit to the Sea*, Proceedings of a symposium held in New Orleans, Louisiana, USA, 11-14 December 2014, IAHS Publ. 367, 163-169.

Banasik, K. & Hejduk, L. (2012). Long-term changes in runoff from a small agricultural catchment. *Soil & Water Res., 7(2)*, 64-72.

Banasik, K., Hejduk, L., Oygarden, L. (Eds), (2011). *Prediction and reduction of diffuse pollution. Solid emission and extreme flows from rural areas – case study of small agricultural catchments*. Warsaw: WULS-SGGW Press.

Banasik, K., Krajewski, A., Sikorska, A. & Hejduk, L. (2014). Curve Number estimation for a small urban catchment from recorded rainfall-runoff events. *Archives of Environmental Protection, 40(3)*, 75-86.

Banasik, K., Madeyski, M., Mitchell J.K., Mori K. (2005). An investigation of lag times for rainfall–runoff–sediment yield events in small river basins. *Hydrological Sciences Journal, 50(5)*, 857-866.

Banasik, K. & Walling, D. (1996). Predicting sedimentgraphs for a small agricultural catchment. *Nordic Hydrology, 27(4)*, 275-294.

Banasik, K., Woodward, D., Hawkins R. (2014). Curve Numbers for Two Agro-Forested Watersheds. *World Environmental and Water Resources Congress 2014: Water without Borders*, 2235-2246. ASCE, Portland, Oregon, June 1-5, 2014.

Bogdanowicz, E., & Stachy, J. (1998). Maksymalne opady deszczu w Polsce. Charakterystyki projektowe (Maximal rainfall in Poland. Design characteristics). *Materiały badawcze. Seria: Hydrologia i Oceanologia, 23*. Warszawa, IMGW.

Hawkins, R.H. (1993). Asymptotic determination of curve numbers from data. *Journal of Irrigation and Drainage Division*, *American Society of Civil Engineers, 119(2)*, 334-345.

Hlavcova, K., Kohnova, S., Kubes, R., Szolgay, J., Zvolensky M. (2005). An empirical method for estimating future flood risk for flood warnings. *Hydrology and Earth System Sciences, 9(4)*, 431-488.

Ignar, S. (1998). The SCS method and its application for effective rainfall determination (in Polish), *Przeglad Geofizyczny (Review of Geophysics), XXXII(4)*, 451-455, 1988.

Karabova, B., Sikorska, A.E., Banasik, K., Kohnova S. (2012). Parameters determination of a conceptual rainfall-runoff model for a small catchment in Carpathians. *Annals of Warsaw University of Life Sciences – SGGW, Land Reclamation, 44(2)*, 155–162.

Krajewski, A., Lee, H., Hejduk, L., Banasik K. (2014). Predicted small catchment responses to heavy rainfalls with SEGMO and two sets of model parameters. *Annals of Warsaw University of Life Sciences – SGGW, Land Reclamation, 46(3)*, 205-220.

Miler, A. (2012). Ocena wpływu zmian użytkowania terenu na odpływy wezbraniowe przy użyciu metody CN – SCS. *Rocznik Ochrona Środowiska, 14*, 512–524.

USDA-Natural Resource Conservation Service (2003). *National Engineering Handbook. Part 630*, *Hydrology*.

Van Mullem, J.A., Woodward D.E., Hawkins R.H., Hjelmfelt A.T., Quan Q.D. (2002). Runoff Curve Number method: Beyond the Handbook". *Proceedings of Second Federal Interagency Hydrologic Modeling Conference*, Las Vegas, Nevada.

Williams, J.R. (1978). A sediment graph model based on the instantaneous unit sediment graph. *Water Recourses Res. 14(4),* 659-664.

Zależność przepływu powodziowego od parametru CN i czasu trwania deszczu w małej zlewni rzecznej

Streszczenie

Przepływy maksymalne o niskim prawdopodobieństwie przewyższenia są potrzebne przy projektowaniu i utrzymaniu budowli wodnych i komunikacyjnych (jazy, zbiorniki, ujęcia wód, mosty, przepusty) oraz w ochronie przed powodziami, w tym również przy tworzeniu map ryzyka powodziowego. W przypadku małych zlewni, zwykle nie posiadających pomiarów hydrometrycznych, podstawowym sposobem wyznaczenia takich przepływów jest zastosowanie modeli opad odpływ. Celem pracy było sprawdzenie reakcji małej, rolniczo-leśnej zlewni nizinnej w postaci hydrogramu odpływu bezpośredniego, na ulewne deszcze o przyjętym 1-procentowym prawdopodobieństwie przewyższenia i różnym czasie trwania, oraz przy różnym potencjale formowania się odpływu bezpośredniego w zlewni, charakteryzowanego parametrem CN. Parametry modelu przyjęto na podstawie wieloletnich badań hydrologicznych przeprowadzonych w badanej zlewni. Parametr CN uzależniono od wysokości opadu i dodatkowo wzięto pod uwagę wpływ niepewności w ustaleniu jego wartości na wynik obliczeń. Parametry chwilowego hydrogramu jednostkowego przyjęto jako stałe we wszystkich scenariuszach obliczeniowych. Przedstawiony w wynikach obliczeń – początkowy wzrost przepływów kulminacyjnych hydrogramów odpływu bezpośredniego, a następnie spadek, wraz ze wzrostem przyjmowanych czasów trwania opadów jest efektem równoczesnego oddziaływania wzrastającej objętości odpływu, z danego opadu i zmniejszającego się natężenia średniego. Wyniki analizy wskazują na wysoką wrażliwość przepływów kulminacyjnych na zmianę parametru CN (zmiana CN o wartość standardowego błędu oceny wywołuję ok. 6% zmianę przepływu kulminacyjnego).

Abstract

Estimations of flood peak discharges of low probability of exceedance are required for designing and maintaining hydraulic and road structures (reservoirs, weirs, water intakes, bridges, culverts) as well as for flood protection, including assessment of the risk of flooding. Rainfall-runoff models are usually the only alternative for such estimations in case of small catchments as there is a lack of sufficient, good quality historic data to be used for applying the traditional i.e. statistical methods. The aim of this study was to check responses of a small agro-forested catchment to rainfall of assumed 1% probability of exceedance and of various duration, and with various potential of the catchment to form runoff, characterize by a changeable Curve Number – CN. Field data of rainfall-runoff events, recorded in the investigated catchment of Zagożdżonka river since 1980, were used to estimate the model parameters. Application of the rainfall-runoff procedure indicated high sensitivity of peak discharge to CN value. A change in CN of the value of standard error of estimation made ca. 6% change in flood flow.

Słowa kluczowe:
modelowanie opad-odpływ, parametr CN, mała zlewnia,
niepewność przepływów obliczeniowych

Keywords:
rainfall-runoff modelling, curve number, small catchment,
design flood uncertainty