ACTA SCIENTIARUM POLONORUM *Acta Sci. Pol., Formatio Circumiectus 6 (2) 2007, 3–17*

FLOW DYNAMICS OF THREE EXPERIMENTAL FORESTED WATERSHEDS IN COASTAL SOUTH CAROLINA (USA)

Devendra M. Amatya[1], Artur Radecki-Pawlik[2]
[1] USDA Forest Service, Center for Forested Wetlands Research, Charleston, SC
[2] Agricultural University of Krakow

Abstract. Three first-, second- and third-order experimental forested watersheds located within the Francis Marion National Forest in the lower coastal plain of South Carolina were monitored for rainfall and stream outflows. The largest watershed (WS 78) with some open lands, roads and wetlands gave higher annual water yields compared to the two other smaller ones (WS 79, WS 80) with mostly forest vegetation, possibly due to a difference in land use, soils and topography as well as increased base flows. Flow duration curves yielded largest flow rates exceeding 4% of the time for the second-order watershed (WS 79). As expected, the daily flows persisted for 79% of the time in the largest 3rd-order watershed (WS 78) with a larger storage compared to only 65 and 60% in the 2nd- and 1st-order watersheds. The flow frequency analysis of peak flows, employing Pearson III-type distribution, revealed the peak flows for 100-, 50-, 25-, 10- and 5-year return periods as 1805, 1565, 1326, 1009 and 769 cfs (cubic feet per second) for WS 78; 379, 325, 272, 200 and 146 cfs for WS 79; and 73, 63, 54, 41 and 32 cfs for WS 80. These results are in good agreement with the data calculated using the USGS-developed formulae for the South Carolina Lower Coastal Plain and have implications for the design of engineering structures, water and nutrient management, as well as evaluation of the impacts of development and natural disturbances on the forested lands of the Atlantic Coastal Plain.

Key words: stream outflow, runoff coefficient, peak flows, flow-frequency-duration, pine forest

INTRODUCTION

Scientists recognise that long-term hydrologic monitoring of watersheds is necessary if they are to understand the basic physical processes governing the dynamics of stream flow, storm events, and their interactions with other hydrologic components such as

Corresponding author − Adres do korespondencji: prof. dr hab. inż. Artur Radecki-Pawlik, Department of Water Engineering, Agricultural University of Krakow, al. Mickiewicza 24/28, 30-059 Krakow, Poland, e-mail: rmradeck@cyf-kr.edu.pl

precipitation, evapotranspiration (ET) and ground water flow (seepage). Furthermore, long-term monitoring provides baseline data for assessing the impacts of natural and anthropogenic disturbance on these processes, conservation of regional ecosystems, generation of scientific hypotheses, and testing of hydrologic and water quality models [Amatya et al. 2005].

Generally, the long-term hydrological observations in a watershed include precipitation, stream water level, flow rate (discharge) and velocity, and ground water level. These observations are essential components for characterizing the watershed hydrology, water budgets, rainfall-runoff relationships, water and water resources management, design of hydraulic structures, and management of eco-hydrology (water quality, vegetation and aquatic habitat). The stream flow dynamics of a watershed is generally characterised by the spatial and temporal distribution of varying flow regimes. The parameters describing the flow dynamics are runoff ratios, maximum peak flow rates, low flow rates, and their temporal distribution, flow frequency and duration, and storm event characteristics. The dynamics of stream flow may be impacted by changes in land use, climate, and other natural and anthropogenic disturbances.

In recent years, land use changes due to timber management and increasing urban development in the Southeastern US, especially in the forested lands of the Atlantic Coastal Plain, have led to studies on the hydrology, water quality and effective management of Southeastern forested ecosystems [Harder et al. 2006]. This landscape is characterised by low-gradient poorly drained soils, where stream flow processes are regulated predominantly by shallow water table positions. In order to address the impacts of forest management (such as harvesting, thinning, prescribed burning, etc.) on stream flow (runoff), soil moisture, and flooding on these coastal plain landscapes, the USDA Forest Service Southeastern Forest Experiment Station (since renamed as the Center for Forested Wetlands Research (CFWR)) in Charleston, SC, had established four experimental watersheds of various sizes (WS 77 − 160 ha, WS 78 – 5000 ha, WS 79 – 500 ha, and WS 80 – 200 ha) within the Francis Marion National Forest (Fig. 1) during the 1960's [Amatya and Trettin 2006]. Various eco-hydrologic studies were conducted by collecting data from these watersheds. Young [1966] reported a two-year water budget for the treatment watershed (WS 77) and concluded that excess water in the form of runoff could be problematic in downstream flooding, and that there was no dependable base flow generated from this natural watershed. Young [1967] also described the flooding pattern, flashiness, and effects of storage on these forested lands in controlling the outflow processes. Data on hydrology, stream flow, water budgets, and water quality for the periods from 1967 to 1979 (pre-Hugo Hurricane) and 1990 to 2001 (post-Hugo) have been published elsewhere [Binstock 1978, Nguyen 1978, Richter et al. 1983, Sun et al. 2000, Miwa et al. 2003, Amatya et al. 2003]. Data from watersheds WS 78 and WS 79 (Fig. 1) have not been previously reported.

The main objectives of this paper are three-fold: (1) to quantify the runoff-rainfall relationships, (2) to derive the flow duration curves, and (3) to estimate the magnitude and frequency of maximum floods and minimum discharges using the historical data measured between 1964 and 1976 in three (first-, second- and third-order) forested watersheds. Statistical tools are used on these long-term hydrological observations to provide a basis for meaningful interpretations of sustainable forest management and decision-making processes for water quantity and quality, including the design of water management structures.

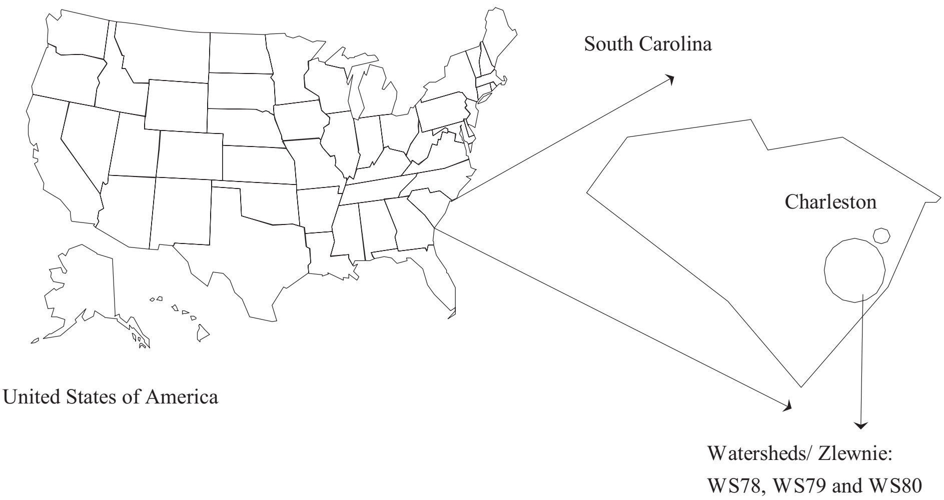

Fig. 1. Location map of three experimental watersheds (WS 78, WS 79, WS 80) in the Santee Experimental Forest in Coastal South Carolina
Rys. 1. Szkic usytuowania zlewni pomiarowych (WS 78, WS 79, WS 80) w Lasach Doświadczalnych Santee w nadatlantyckiej części Południowej Karoliny

MATERIAL AND METHODS

Description of catchments

WS 80. The watershed, first delineated in 1968, drains a first-order headwater stream and is contained within the Santee Experimental Forest near Huger in South Carolina. This site serves as the control watershed for a paired watershed system that includes a treatment watershed (WS 77) [Young and Klaiwitter 1968, Harder 2004]. WS 80 is 200 ha in size and has not been managed for over eighty years. The first-order stream flows into Fox Gulley Creek (WS 79), then into Turkey Creek (WS 78), a tributary of Huger Creek, which drains ultimately into the Cooper River, an estuarine river of the Atlantic Ocean. The total length of the perennial stream is 1375 m and the relief at the site is about 6 m. After Hurricane Hugo in 1989, natural regeneration resulted in three general forest canopy types: pine-hardwood (39%), hardwood-pine (28%) and mixed hardwoods (33%). The study site consists of primarily moderately drained sandy loam soils with poorly drained clayey subsoils of the Wahee (*Thermic Aeric Ochraquults*)-Lenoir (*Thermic Aeric Paleaquults*)-Duplin (*Thermic Aquic Paleudults*) association [Harder 2004, Harder et al. 2006].

WS 79. This is a second-order watershed with a 1640 m-long stream channel draining Fox Gulley Creek, which contains both watersheds WS 77 and WS 80 as well as a part between them (Fig. 1). The watershed with a drainage area of approximately 500 ha is located within the Santee Experimental Forest. The soils in this watershed (Lenoir, Meggett, Duplin and Craven) all are clays ranging from poorly to moderately well drained. The impressive size of the relict (pre-Hugo) pines and hardwoods as well as the rapid growth of the post-Hugo natural regeneration (pine and hardwood) attest to high productivity of the soils [Dupre 2005, personal communications]. The elevations at the site vary from 3 to 10 m a.m.s.l .

WS 78. The third-order watershed (also called Turkey Creek) with a stream channel length of 11.4 km over a relief of 3 to 12 m a.m.s.l. draining approximately 5000 ha of the Francis-Marion National Forest (Fig. 1). The land use within the watershed comprises 52% forest (mostly regenerated loblolly pine (*Pinus taeda* L.) and long-leaf pine (*Pinus palustris*) within the Francis-Marion National Forest), 28% wet shrubs and scrubs, 14% wetlands and water, with the remaining 6% developed for agricultural lands, roads and open areas. The forest area was almost completely damaged by Hurricane Hugo in September 1989. The watershed is dominated by poorly drained clayey soils of Lenoir-Lynchburg (*Thermic Aeric Paleaquults*) series followed by some sandy and loamy soils.

Hydrologic measurements

Rainfall was measured using a manual gauge at the weather station located within the Santee Experimental Forest Headquarters, which is about 2 km from the watershed WS 80 (Fig. 1). The weather station comprising a rain gauge and temperature recorder installed in 1946 was upgraded to an automatic one (Campbell Scientific CR-10X) in 1996. Additional manual rain gauges recording on a weekly basis have been distributed over the watersheds since 1964 but data from only one continuous recorder were used in this study; at present there are five automatic tipping bucket gauges with electronic data-loggers.

Stream flows

WS 80. The gauging station at the outlet of this watershed consists of a compound V-notch weir and a flat crested weir installed under the Yellow Jacket Road Bridge, and a gauge house with a stage recorder (Fig. 1). The stage (water level) measured above the bottom of the V-notch weir was used to estimate the flow rate using standard weir equations. Flows on this watershed were monitored from 1968 to 1981 and did not start again until after Hurricane Hugo in November 1989. Since then the flow monitoring has been ongoing. Details of the outlet type and methods of flow estimates are given elsewhere [Young 1967, Harder 2004].

WS 79. The outlet of this second-order watershed comprises a compound V-notch weir in the middle with two rectangular concrete box culverts on either side. The bottom of each culvert is flushed with the top of the V-notch weir allowing to measure large outflows through the culverts after the V-notch weir is full. The outlet structure is located under the bridge of Lotti Road, a boundary of the watershed (Fig. 1). The gauge house is located on the left bank. Stage levels on this watershed were monitored between 1966 and 1973 and did not start again until 1996. Stage-discharge rating curves were developed to estimate the flow rates using the stage data.

WS 78. The original outlet for the gauging station on this watershed was located about 800 m downstream of the existing Turkey Creek Bridge on Highway 41 N near the town of Huger, SC. The abandoned outlet comprising a gauge house on the left bank and the openings at various levels of an embankment measured stages of the stream from 1964 to 1984 [Young 1965]. Stage-discharge rating curves were developed to estimate the stream flow rates. Under a recent cooperative agreement with the Forest Service, Atlanta-based Tetra-Tech, Inc. helped digitise the historical stream flow data recorded on the strip-charts. A new stream gauging station has recently been established slightly upstream of the old abandoned station by the collaboration with USGS and College of Charleston [Amatya and Trettin 2006].

Most of the stage data recorded from 1960s to mid-1990s, until the new electronic data loggers were installed, were on magnetic punch tapes, which were digitised at the USDA Forest Service Coweeta Hydrologic Laboratory in NC. Measured stage elevations were processed with SAS programs to compute flow rates. In this study, stream flow rates only from 1964 to 1976 for all watersheds were integrated into daily watershed depth-based outflows using the corresponding watershed areas for further analyses. Annual runoff-rainfall ratios were computed dividing measured annual stream flow (runoff) by rainfall for each of the watersheds. Flow duration curves for all three watersheds were derived using daily stream flow data. These graphical plots illustrate the percent time flow exceeds or equals a certain value of interest. The slopes of these curves can also be used to characterise the flashiness and base flows.

Flood frequency analysis

This analysis was conducted to determine *T*-year floods and discharges − the discharges that appeared in the research cross-section − with a certain probability of occurrence.

The most common and frequent uses of statistics in hydrology have been that of frequency analysis. The goal of the frequency analysis is to estimate the magnitude of an event having a given frequency of occurrence or to estimate the frequency of occurrence of an event having a given magnitude [Haan 2002]. The frequency is often stated in terms of return period, T (in years), or a probability of occurrence in any one year, p. Hydrologic frequency analysis can be made with or without making any distributional assumption. In the present paper the authors used two different distributional assumptions: the one for maximum floods (Pearson III distribution) and the second for minimum discharges (Gumbel distribution). If a distributional assumption is made, the magnitude of events for various return periods is selected from the theoretical "best-fit" line according to the assumed distribution.

When we do not have hydrological observations for a certain period of time or the adequate long-time series, we could use regional formulae to calculate the *T*-year floods (obviously it is possible if such formulae exist for the study region). We also very often do such calculations to compare the results from different methods (in this case having distributional analysis) to obtain a better understanding of the flow dynamics of watersheds. In the present paper, all methods mentioned above were used to calculate maximum floods and minimum discharges.

Lower Coastal Plain formulae for maximum floods

To provide simple methods of estimating flood peak discharges, the US Geological Survey has developed and published regional formulae for every state including the State of South Carolina. In 1993, the USGS in cooperation with the Federal Emergency Agency and the Federal Highway Administration prepared and compiled all equations from all

US to one computer program, entitled the National Frequency Program [US Geological Survey 2000]. The State of South Carolina was divided into four regions: Blue Ridge, Piedmont, Upper Costal Plain and Lower Costal Plain. All areas were divided into rural and urban. Since the watersheds studied herein which are located in rural areas of the Lower Costal Plain region, the following formulae were used to estimate *T*-year floods [Guimares and Bohan 1992, US Geological Survey 2000]:

$$Q_2 = 56A^{0.63},\quad Q_5 = 111A^{0.61},\quad Q_{10} = 157A^{0.59},\quad Q_{25} = 221A^{0.59}$$
$$Q_{50} = 275A^{0.58},\quad Q_{100} = 335A^{0.58},\quad Q_{500} = 569A^{0.52}$$

For South Carolina, the regression equations were developed from peak discharges monitored through 1988 in 52 stream gauging stations. However, there are some restrictions on the application of these formulae (such as the limitation of the area and certain locations within the state) but they are not pertinent to the research area covered in this paper.

RESULTS AND DISCUSSION

Runoff-rainfall relationships

WS 80. The computed runoff-rainfall ratios for this 1st-order watershed for the period of 1969 to 1976 varied from 16% in 1972 to 29% in 1971 (Fig. 2) for the rainfall of 1106 mm and 1694 mm, respectively. These ratios corresponded to the depth-based stream flows of 175 mm in 1971 to 499 mm in 1972. The average ratio was computed to be 21%. There was more variability in annual runoff (coefficient of variation, CV = 0.33) compared to the annual rainfall (CV = 0.14) for the same period. The computed runoff-rainfall ratios for this watershed with a matured pine and hardwood mixed forest before the impact of Hurricane Hugo are consistent with those for similar other naturally drained forested watersheds in the coastal plain [Chescheir et al. 2003].

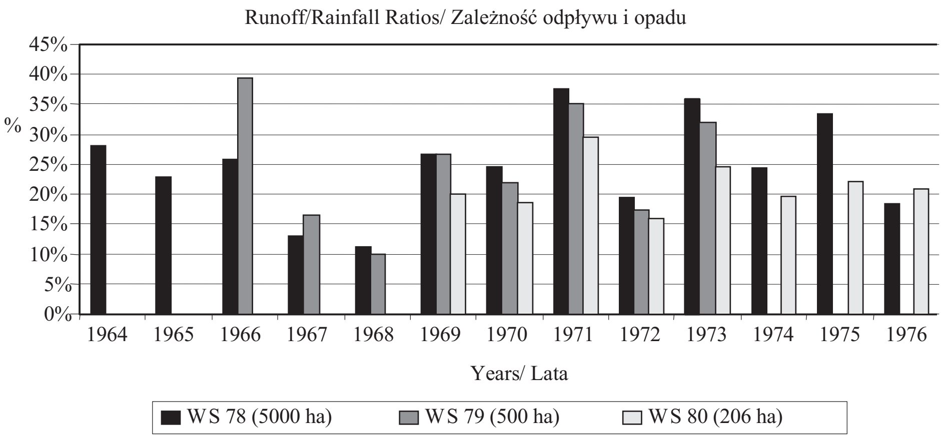

Fig. 2. Annual runoff ratio as a percentage of rainfall for three watersheds (1964−1976)
Rys. 2. Odpływ roczny wyrażony w procentach opadu dla badanych zlewni (1964−1976)

WS 79. The maximum and minimum runoff ratios observed during 1966 to 1973 for this 2nd-order watershed were 10% in 1968 with 1141 mm of rainfall to 40% in 1966 with 1505 mm of rainfall with an average of 25%. These ratios corresponded to annual runoff of 114 mm and 599 mm. As on WS 80, the runoff was much more variable (CV = 0.54) than the rainfall (CV = 0.17). Although the maximum rainfall measured was 1694 mm in 1971, the runoff coefficient was only 35%. This indicates that the dry antecedent conditions in the later part of 1970 (Fig. 2). Although WS 80 is also a part of WS 79, one reason for its higher runoff coefficient compared to WS 80 may be due to various types of disturbances that had occurred on the treatment watershed WS 77 with an area of 160 ha, contained within this watershed WS 79.

WS 78. This third-order largest watershed yielded the runoff ratios ranging from 11% in 1968 with a rainfall amount of 1141 mm to as much as 38% in 1971 with an annual rainfall of 1694 mm with an average of 25% for the 13-year (1964–1976) period (Fig. 2). Again, the computed CV of 0.45 for the runoff was much higher than the CV of 0.18 for the measured rainfall. Note that the CV for the rainfall for this 5000 ha watershed was computed using data from only one gauge. Rainfall in this region has been reported to have a large spatial variability, especially during summer tropical storms [Richter et al. 1983, Harder 2004, Amatya et al. 2002].

When the runoff ratios were compared across the same 5-year period (1969–1973) (Fig. 2), the largest watershed WS 78 consistently yielded the highest values (average = 29%) followed by the second largest WS 79 (average = 27%) and the smallest WS 80 (average = 22%). However, the difference between WS 78 and WS 79 was much smaller compared to the difference between WS 79 and WS 80. Again, this 5% increased runoff depth may be explained by some treatments done on a part (WS 77) of WS 79. Interestingly, the CV for annual outflows was nearly the same for all three watersheds: 0.40, compared to 0.16 for rainfall.

The daily cumulative stream flow dynamics for the three watersheds are compared for the same five-year period in Figure 3. Clearly, the daily cumulative flow indicated the least

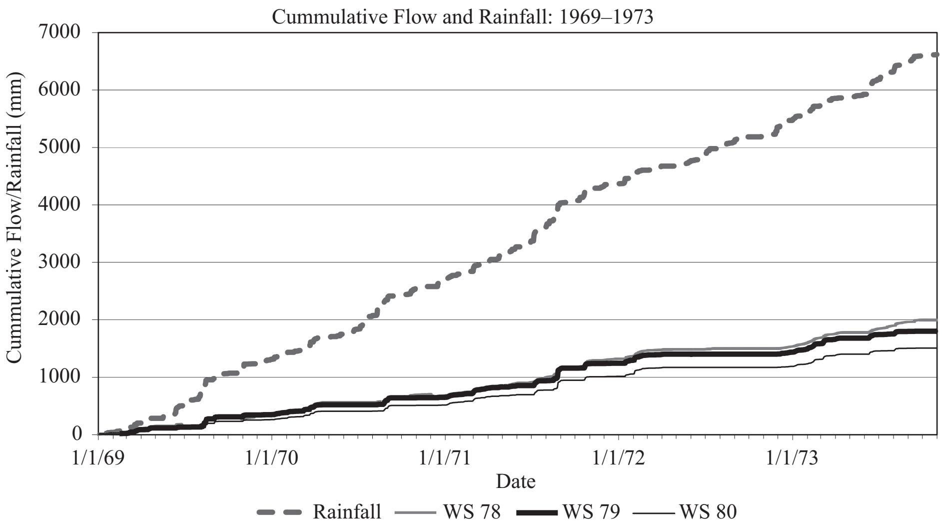

Fig. 3. Daily cumulative rainfall and stream flow for three watersheds (1969−1973)
Rys. 3. Dzienny skumulowany opad i odpływ dla trzech badanych zlewni (1969−1973)

response (lower runoff) to rainfall for the smallest watershed (WS 80) compared to the other two larger watersheds. The total cumulative outflow was smallest (1506 mm) for the smallest watershed WS 80 and the largest (1996 mm) for the largest watershed WS 78. The cumulative outflow of 1802 mm from the second largest watershed WS 79 was only 20% higher than the total of 1506 mm for the smallest watershed WS 80. However, the largest outflow of 1996 mm from WS 78 was only about 11% higher than that from WS 79.

Assuming that evapotranspiration (ET) is the dominant component of water loss, followed by stream flow (runoff) on this humid, poorly drained coastal plain, the smallest watershed WS 80, with an average runoff ratio of 22%, might have lost almost 78% of the rainfall to ET. Similarly, the ET losses from the watersheds WS 79 and WS 78 were estimated to be 73% and 71%, respectively, of the total rainfall. The ET losses of 71% (972 mm on average), 73% (993 mm on average) and 78% (1032 mm on average) of the total rainfall of 6617 mm for the 5-year period for WS 78, WS 79 and WS 80 are consistent with the average annual estimated ET of about 1000 mm or more for the area [Young and Klaiwitter 1968, Harder 2004].

It can be generally argued that the annual stream flows from large watersheds may be somewhat higher for reasons such as large topographic gradient and base flows, and spatial heterogeneity in land use, soils and vegetation [Amatya et al. 2002]. Especially, in the case of the watershed WS 78 (Turkey Creek), both the average gradient and base flows may be somewhat higher than that for both WS 79 and WS 80. Most importantly, this watershed has some parts of the land that are developed such as roads, buildings, agricultural lands and open areas, all of which contribute to higher runoff. A very large area of the watershed on poorly drained clayey soils, especially on the right bank and at the headwaters, also may contribute to larger runoff. Furthermore, unlike WS 79 and WS 80, which are both mature forests within the Santee Experimental Forest, some of the forested lands on the large watershed WS 78 within the Francis-Marion National Forest, may have been in various treatments such as thinning, burning, clear-cut and open lands. The other possible source of error may be in measured depth-based flows, which are dependent on the measured drainage area. The accurate measurement of drainage area on the flat land like this is a challenging task. The problem may even more be exacerbated during large storm events when the water table is on the surface which may cause surface runoff across the watershed boundary.

Flow duration analysis

The daily flow duration curves derived using the measured daily depth-based stream flow data from all three watersheds (WS 78, WS 79 and WS 80) for the five-year (1969–1973) period are presented in Figure 4. A median plotting position was used to estimate the exceedance probability. The steeper slopes at the higher ends of the curves (for 2% of the time) for the watersheds WS 79 and WS 80 indicate their flashiness compared to the largest watershed WS 78. Apparently, the highest flows that occurred during this period were 85 mm on WS 79, 49 mm on WS 80, and 32 mm on the largest watershed WS 78. A daily flow of 10 mm or higher exceeded almost 0.8% of the time (14 out of 1765 days) on all watersheds with the watershed WS 79 yielding the highest (20 mm), followed by WS 80 (15.5 mm) and WS 78 (10 mm). The daily flow on the second-order watershed

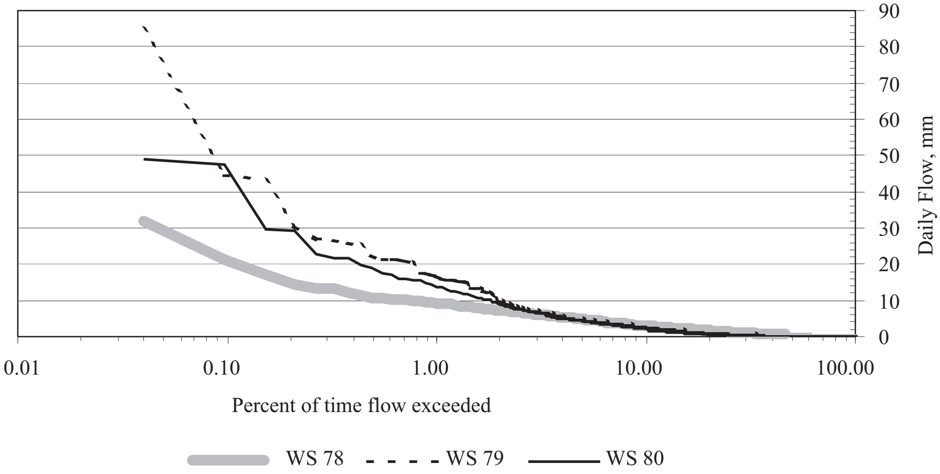

Fig. 4. Daily flow duration curves for three watersheds (1969−1973)
Fig. 4. Krzywe czasów trwania przepływu dla trzech badanych zlewni (1969−1973)

WS 79 exceeded the flows on two other watersheds for nearly 4% of the time. The first-order watershed (WS 80) yielded flows only 60% of the time whereas the flows exceeded zero values for 65% and about 79% of the time for the second- (WS 79) and third-order (WS 78) watersheds. The median (50-percentile) daily flows for the watersheds WS 80, WS 79 and WS 78 were 0.05, 0.09 and 0.45 mm, respectively. This is generally expected because as the watershed size grows, the stream flow occurs for an extended period of time possibly due to increased base flows. Similarly, the largest watershed WS 78 substantially dampened the peak flows exceeding 32 mm due to large surface storage.

Interestingly, the largest peak flows of 85 and 49 mm on the watersheds WS 79 and WS 80 occurred on August 26, 1971 as a result of 198 mm of rain on four consecutive days with already wet conditions caused by 79 mm of rain prior to that event. However, that large event did not cause the highest peak on the watershed WS 78, possibly due to the spatial variability of rain on this largest watershed. The two highest flow rates on WS 79 and WS 80 and one highest on WS 78 occurred in the same August of 1971 that measured 416 mm of rain.

One of the main reasons for the slightly higher frequency and magnitude of larger flow rates on the second-order watershed WS 79 (500 ha) compared to the 206 ha first-order watershed (WS 80) could be due to the much higher outflows contributed by a part (WS 77 of 160 ha area) of this watershed compared to WS 80 also located within WS 79 (Fig. 1). Gilliam [1983] reported a large difference in seasonal and annual outflows between WS 77 and WS 80 with higher flows for the WS 77 during their study period of 1976–1980. The author, citing Richter [1983], also concluded that this difference could have been due to differential deep seepage, large vegetational difference affecting the ET, incorrect hydrologic boundary delineation as well as calibration errors in the measurements of flows. Similar discrepancies in flows between the watersheds WS 80 and WS 77 for 1969−1976 period were reported by Nguyen [1978].

Flood frequency analysis

The results of calculations and analysis are presented in the following manner: first, the maximum floods calculated using the Pearson-III distribution for all three watersheds are shown in Tables 1, 2 and 3, next, the results of calculations using regional formulae are given in Table 4.

Table 1. Maximum floods for watershed WS 78 obtained using Pearson-III distribution
Tabela 1. Przepływy maksymalne dla zlewni WS 78 obliczone za pomocą rozkładu Pearsona-III

Probability of flow Prawdopodobieństwo przepływu	Return period, years Okres powtarzalności, lata	Predicted flow value, cfs* Przewidywana wartość przepływu, cfs*	Standard terror, cfs Błąd standardowy, cfs
0.995	200	1756	505
0.990	100	1613	418
0.980	50	1464	336
0.960	25	1307	261
0.900	10	1080	179
0.800	5	886	137
0.667	3	719	121
0.500	2	560	112

* cfs = $ft^3 \cdot s^{-1}$

Table 2. Maximum floods for watershed WS 79 obtained using Pearson-III distribution
Tabela 2. Przepływy maksymalne dla zlewni WS 79 obliczone za pomocą rozkładu Pearsona-III

Probability of flow Prawdopodobieństwo przepływu	Return period, years Okres powtarzalności, lata	Predicted flow value, cfs Przewidywana wartość przepływu, cfs	Standard terror, cfs Błąd standardowy, cfs
0.995	200	540	560
0.990	100	441	367
0.980	50	351	244
0.960	25	268	202
0.900	10	175	199
0.800	5	119	161
0.667	3	89	93
0.500	2	73	16

Table 3. Maximum floods for watershed WS 80 obtained using Pearson-III distribution
Tabela 3. Przepływy maksymalne dla zlewni WS 80 obliczone za pomocą rozkładu Pearsona-III

Probability of flow Prawdopodobieństwo przepływu	Return period, years Okres powtarzalności, lata	Predicted flow value, cfs Przewidywana wartość przepływu, cfs	Standard terror, cfs Błąd standardowy, cfs
0.995	200	81	30
0.990	100	73	24
0.980	50	65	18
0.960	25	57	13
0.900	10	46	8
0.800	5	38	6
0.667	3	31	5
0.500	2	24	5

Table 4. Maximum floods for three watersheds obtained using regional formulae for South Carolina, Lower Costal Plain (rural areas)
Tabela 4. Przepływy maksymalne dla badanych zlewni obliczone za pomocą regionalnych wzorów dla nadmorskiej równiny w Południowej Karolinie (dla terenów rolniczych)

Probability of flow Prawdopodobieństwo przepływu	Return period, years Okres powtarzalności, lata	WS 78	Predicted flow value, cfs Przewidywana wartość przepływu, cfs WS 79	WS 80
0.999	500	2653	801	505
0.990	100	1865	491	293
0.980	50	1531	403	241
0.960	25	1268	326	194
0.900	10	900	231	137
0.800	5	675	166	97
0.500	2	418	85	49

SUMMARY AND CONCLUSIONS

A study was conducted to examine the stream flow dynamics of three experimental forested watersheds (1st order, WS 80 – 200 ha; 2nd order, WS 79 – 500 ha; and 3rd order, WS 78 – 5000 ha) located within the Francis Marion National Forest in coastal South Carolina. Historical precipitation and stream flow (runoff) data measured during 1964 to 1976 before Hurricane Hugo (1989) were used to derive annual rainfall-runoff ratios, daily cumulative flows and flow duration curves, and to perform a flood frequency analysis for these watersheds. The results showed that the variability of annual runoff on all watersheds was much higher than that of rainfall. When the data were compared for the same five-year period, the coefficient of variation in the annual runoff was the same for all watersheds: 0.40, compared to only 0.16 for the annual rainfall. The average annual runoff computed as a percentage of rainfall for the same period was the highest (29%) for the 3rd-order watershed (WS 78) followed by the 2nd-order watershed WS 79 (27%) and the 1st-order watershed WS 80 (22%). The increase in runoff on WS 79 compared to WS 80 was possibly due to the difference in vegetation, reduced seepage losses, impervious areas like roads and even errors in flow calibration. Similarly, the largest cumulative outflow of 1996 mm on the 3rd-order watershed (WS 78) was attributed to varying land use and soils effects, ground water inputs, and variability in rainfall. Although the annual runoff coefficients presented here may provide insight into the average watershed response and stream flow dynamics, they may not sufficiently capture the dynamics of runoff generation processes in which case seasonal dynamics are recommended. Srinivasan et al. [2005] recently demonstrated a need of seasonal prediction of runoff dynamics for understanding the phosphorus transport process.

The flow duration data indicated some flashiness (higher peak flows) of the smaller watersheds compared to the largest watershed WS 78. The daily flows on WS 78 occurred for 79% or more time compared to only 65 and 60% for WS 79 and WS 80, respectively. Also, for about 4% of the time the daily flows on the second-order watershed WS 79 were higher than those from two other watersheds. The median (50-percentile) daily flows were 0.05, 0.09 and 0.45 mm for WS 80, WS 79, and WS 78, respectively. The flow frequency analysis with 13, 7 and 13 years of peak flows for WS 78, WS 79 and WS 80, respectively, employing the Pearson III-type distribution revealed the peak flows for 100-, 50-, 25-, 10- and 5-year return periods as 1805, 1565, 1326, 1009 and 769 cfs for WS 78; 379, 325, 272, 200 and 146 cfs for WS 79; and 73, 63, 54, 41 and 32 cfs for WS 80. These results are in good agreement with the data calculated using the USGS-developed formulae for South Carolina Lower Coastal Plain.

The stream flow data currently being collected at the new USGS gauging site on the Turkey Creek watershed (WS 78) and our continuing flow measurements on the watersheds WS 79 and WS 80 will provide insight about runoff-rainfall relationships among these watersheds after the impacts of Hurricane Hugo. The historical data from the Turkey Creek watershed along with aerial photographs for successive years are also being used to evaluate the effects of land use change and the hydrologic effects of Hurricane Hugo in September 1989. Studies are also underway to determine the stream hydrograph characteristics of these watersheds. These data from predominantly forested watersheds may serve as reference levels for designing water management structures, evaluating the impacts of land management and development on hydrology and water quality, and recommending best management practices on these lower coastal plain watersheds.

Acknowledgements

This work was made possible by the support from the USDA Forest Service Southern Research Station and NCASI, Inc. The authors would like to acknowledge Dr. Carl Trettin, Project Leader at CFWR, for reviewing the paper; Dr. Timmothy Callahan at the College of Charleston for research collaboration and the review of the paper; Lisa Wilson, graduate student at the College of Charleston, for GIS and flow data acquisition and processing; John Dupre and Marie Butler at the Francis-Marion National Forest for GIS data from the Turkey Creek watershed (WS 78); Jamie Miller at Tetra-Tech, Inc. for digitising the WS 78 flow data; and the USGS District Office in Columbia for cooperation in the establishment of a new gauging station in WS 78.

REFERENCES

Amatya D.M., Chescheir G.M., Skaggs R.W., Fernandez G.P., 2002. Hydrology of poorly drained coastal watersheds in Eastern North Carolina. ASAE Paper No. 022034, St. Joseph, MI.

Amatya D.M., Sun G., Trettin C.C., Skaggs R.W., 2003. Long-term forest hydrologic monitoring in Coastal Carolinas. Proceedings of the 1st Interagency Conference on Research in the Watersheds, 27−30 October 2003, US Department of Agriculture, Agricultural Research Service, 279−285.

Amatya D.M., Trettin C.C., 2006. Development of watershed hydrologic research at Santee Experimental Forest, Coastal South Carolina. Proceedings of the USDA Forest Service Physical Scientists Conference, 18−22 October 2004, San Diego, CA (in press).

Amatya D.M., Trettin C.C., Skaggs R.W., Burke M.K., Callahan T.J., Sun G., Nettles J.E., Parsons J.E., Miwa M., 2005. Five hydrologic studies conducted by or in cooperation with the Center for Forested Wetlands Research, USDA Forest Service. Research Paper SRS-40, USDA Forest Service, Southern Research Station, Asheville, NC.

Byczkowski A., 1972. Hydrological basis of water reclamation designing − extreme hydrological events (in Polish). PWRiL Warszawa.

Chescheir G.M., Lebo M.E., Amatya D.M., Hughes J., Gilliam J.W., Skaggs R.W., Herrmann R.B., 2003. Hydrology and water quality of forested lands in Eastern North Carolina. Research Bulletin No. 320, North Carolina State University, Raleigh, NC.

Chow V.T., 1969. Handbook of applied hydrology. Section 8. McGraw-Hill New York − London −St. Louis − Johannesburg.

Gilliam F.S., 1983. Effects of fire on components of nutrient dynamics in a Lower Coastal Plain watershed ecosystem. PhD thesis. Duke University, Durham, NC.

Guimares W.B., Bohan L.R., 1992. Techniques for estimating magnitude and frequency of floods in South Carolina. US-Geological Survey Water Resources Investigations Report 92-4040.

Haan C.T., 2002. Statistical methods in hydrology. 2nd ed. Iowa State Press, Blackwell Publishing Company, [… USA].

Harder S.V., 2004. Hydrology and water budget of a first order forested watershed in Coastal South Carolina. MSc thesis. College of Charleston, Charleston, SC.

Harder S.V., Amatya D.M., Callahan T.J., Trettin C.C., Hakkila J., 2006. Hydrology and water budget for a forested Atlantic Coastal Plain watershed. J. Amer. Wat. Res. Ass. (tentatively accepted).

Miwa M., Gartner D.L., Bunton C.S., Humphreys R., Trettin C.C., 2003. Characterization of headwater stream hydrology in the southeastern lower coastal plain. Project Report to US EPA, USDA Forest Service, Charleston, SC.

Nemec J., 1972. Engineering hydrology. McGraw-Hill London.

Nguyen V.P., 1978. Effects of a prescribed winter burn on cation budgets of a forested watershed. PhD thesis. Duke University, Durham, NC.

Richter D.D., 1980. Prescribed fire: Effects on water quality and nutrient cycling in forested watersheds of the Santee Experimental Forest in South Carolina. PhD thesis. Duke University, Durham, NC.

Richter D.D., Ralston C.W., Harms W.R., 1983. Chemical composition and spatial variation of bulk precipitation at a coastal plain watershed in South Carolina. Wat. Res. Res. 19, 134−140.
Srinivasan M.S., Gerard-Marchant P., Veith T.L., Gburek W.J., Steenhuis T.S., 2005. Watershed scale modeling of critical source areas of runoff generation and phosphorus transport. J. Amer. Wat. Res. Ass. 41 (2), 361−375.
Sun G., Lu J., Gartner D., Miwa M., Trettin C.C., 2000. Water budgets of two forested watersheds in South Carolina. Proceedings of the Spring Special Conference of the American Water Resources Association 2000, [...]
US Geological Survey, 2000. The National Flood Frequency Program − methods for estimating flood magnitude and frequency in rural and urban areas in South Carolina. US Department of Interior, USGF Fact Sheet 001-00, January 2000.
Wanielista M.P., Kersten R., Eaglin R., 2003. Water quantity and quality control. 2nd ed. John Wiley and Sons London − Sydney − New York.
Young C.E., 1965. Precipitation-runoff relations on small forested watersheds in the coastal plain. Study Plan Addendum No. 1, 4300 Wetland Hydrology Study W-3, FS-SE-1602, Southeastern Forest Experiment Station, Charleston, SC.
Young C.E. Jr., 1966. Water balance on a forested watershed in the flatwoods. Proceedings of the 63rd Annual Convention of the Association of Southern Agricultural Workers, Jackson, MS, 7−9 February 1966, 69.
Young C.E. Jr., 1967. Streamflow – an important factor in forest management in the coastal plain. South. "Lumberman", Christmas Issue, 215 (2680), 109−110.
Young C.E. Jr., Klaiwitter R.A., 1968. Hydrology of wetland forest watersheds. Proceedings of the CUCOH Hydrological Conference, Clemson University, 28−29 March 1968, 29−38.

DYNAMIKA PRZEPŁYWU W TRZECH EKSPERYMENTALNYCH ZLEWNIACH LEŚNYCH W NADATLANTYCKIEJ CZĘŚCI POŁUDNIOWEJ KAROLINY (USA)

Streszczenie. Na terenie trzech eksperymentalnych zlewni leśnych pierwszego, drugiego i trzeciego rzędu usytuowanych we Francis Marion National Forest w Południowej Karolinie (USA) prowadzono obserwacje opadów oraz przepływów rzecznych. Największa zlewnia (WS 78), gdzie oprócz lasów występują tereny otwarte, drogi i mokradła, cechowała się większym spływem niż dwie mniejsze zlewnie (WS 79, WS 80) w większości pokryte lasem. Mogło to być spowodowane odmiennym sposobem użytkowania ziemi, rodzajem gleb, topografią terenu oraz większymi przepływami […?] podstawowymi. Dzienne przepływy w zlewni 3. rzędu (WS 78), największej, o wyższej retencji, występowały przez 79% czasu w roku, a w zlewniach 2. i 1. rzędu − odpowiednio przez 65 i 60% czasu. Przez ok. 4% czasu w roku przepływy dzienne w średniej zlewni (WS 79) były wyższe niż w pozostałych zlewniach. Przepływy maksymalne o 100-, 50-, 25-, 10- i 5-letnim okresie powtarzalności, określone na podstawie analizy częstości przepływów przeprowadzonej z zastosowaniem rozkładu Pearsona III typu, wynosiły odpowiednio 1805, 1565, 1326, 1009 i 769 cfs (stóp sześciennych na sekundę) dla zlewni WS 78, 379, 325, 272, 200 i 146 cfs dla zlewni WS 79 oraz 73, 63, 54, 41 i 32 cfs dla zlewni WS 80 i były zbliżone do wartości przepływów prawdopodobnych obliczonych za pomocą wzorów opracowanych przez służby geologiczne USA (USGS) dla nizinnej części Południowej Karoliny przyległej do Oceanu Atlantyckiego. Wyniki badań będą przydatne w projektowaniu budowli hydrotechnicznych, a także w ocenianiu wpływu czynników naturalnych oraz zagospodarowania terenu na zalesione obszary Niziny Atlantyckiej.

Słowa kluczowe: odpływ w cieku, współczynnik spływu, przepływy maksymalne, częstość przepływu, las sosnowy

Accepted for print − Zaakceptowano do druku: 7.11.2006