Available online at www.sciencedirect.com
SCIENCE DIRECT®
Forest Ecology and Management 214 (2005) 170–182
Forest Ecology and Management
www.elsevier.com/locate/foreco

Defining perennial, intermittent, and ephemeral channels in Eastern Kentucky: Application to forestry best management practices

J.R. Svec [a], R.K. Kolka [b,*], J.W. Stringer [a]

[a] Department of Forestry, University of Kentucky, Lexington, KY 40546, USA
[b] USDA Forest Service, North Central Research Station, Grand Rapids, MN 55744, USA

Received 3 September 2004; received in revised form 9 April 2005; accepted 11 April 2005

Abstract

Typically, Forestry Best Management Practices (BMPs) that are applied to riparian areas are dependent upon stream flow duration. Definitions vary but most often perennial, intermittent and ephemeral channels are classified and used to determine the specific BMP prescription for a site. The most common technique to determine stream class is to use USGS Quadrangle "blue line" maps where blue lines are considered perennial, dashed blue lines are considered intermittent, and ephemeral channels occur where there is convergent topography but no lines are present. This research and others indicate that the "blue line" method is highly inaccurate at the site scale, especially for lower flow systems. In this study we use the channel geometry method and watershed characteristics to develop multiple regression models to predict flow duration across the range of channels in the Eastern Coalfield Region of Eastern Kentucky, USA. Based on our set of predictive models, we can explain 78–91% of the observed variability in flow duration. Parameters that were most common in the models included the natural log of watershed area, bankfull width, width:depth ratio, stream slope and entrenchment ratio. By utilizing our most encompassing model (all sites for their longest time period), we were able to develop a table of general guidelines that classified >95% of study channels correctly. Given the high predictive capability of our models and the geographic range of sites, we believe that our table of guidelines is robust for the Eastern Coalfield Physiographic Region of Eastern Kentucky.

Keywords: Stream flow duration; Forest hydrology; Stream geomorphology; Forest management; Stream classification

1. Introduction

To effectively address non-point source pollution during silvicultural operations and timber harvesting, forest managers and operators must be able to properly classify streams based on flow duration. Typically, the

* Corresponding author. Tel.: +1 218 326 7115; fax: +1 218 326 7123.
E-mail address: rkolka@fs.fed.us (R.K. Kolka).

0378-1127/$ – see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.foreco.2005.04.008

Best Management Practices (BMPs) applied are dependent on whether a channel's flow duration is classified as ephemeral, intermittent or perennial. In Kentucky, as in many other states, the presence, width, and amount of disturbance allowed within the riparian zone, as well as the distance to major soil disturbances (e.g. roads), are all dependent on stream flow duration. Generally, as flow duration increases the potential for non-point source pollution increases, and BMPs intensify to protect water quality. Incorrectly determining stream class can lead to either increased non-point source pollution from increased activity where flow duration would dictate less disturbance, or costly deferral of revenue from the too stringent application of the BMPs.

Currently, Kentucky Forestry BMP guidelines define stream classes as follows (Stringer and Perkins, 2001):

Perennial: streams that hold water throughout the year.
Intermittent: streams that hold water during wet portions of the year.
Ephemeral: a channel formed by water during or immediately after precipitation events as indicated by an absence of forest litter and exposure of mineral soil.

These definitions are similar to many states and guidebooks that use general descriptions of stream class (Stringer and Thompson, 2000; Helms, 1998). In some instances stream class definitions are vague or absent.

For example, Nebraska Forestry BMPs state:

"One of the best ways to protect water quality and other watershed values is to establish Streamside Management Zones (SMZs) beside perennial streams. Intermittent streams, which may flow only during or immediately after a rain, normally do not require this level of protection."

However, no definition of the stream classification is provided (Nebraska Forest Service, 1998). Alternatively, other states provide quantitative definitions of stream class. Texas defines perennial streams as flowing for greater than 90% of the time, intermittent streams as flowing between 30 and 90% of the time and ephemeral channels as those flowing less than 30% of the time (Texas Forest Service, 2000). Other literature shows further discrepancies in stream class definitions. Hedman and Osterkamp (1982) defined perennial streams as those having measurable discharge 80% of the time, intermittent 10–80% of the time, and ephemeral <10% of the time, while Hewlett (1982) defined perennial streams as having water present >90% of the time. A review of BMP guidelines and stream class definitions, on a national scale, indicates the importance and difficulty of proper stream classification for BMP application.

The most common method used by forest operators for determining stream class is the use of US Geological Survey (USGS) Quadrangle "blue line" maps. Solid blue lines are considered perennial; broken blue lines, intermittent; and ephemeral channels are not directly marked but can be inferred from contour patterns and knowledge of local hydrology. The USGS focuses its' monitoring efforts on perennial streams to produce flood and water supply information and seldom monitors intermittent or ephemeral streams. The map delineation between perennial-intermittent and intermittent-ephemeral streams is based on regional models and a landscape-level understanding of hydrologic systems. For regional or state-wide applications this scale may be adequate but for site-specific assessment the reliability is certainly questionable.

Inaccuracies can be seen when measured flow duration data are compared with the USGS map classification. Long-term flow and stage height measurement at the University of Kentucky's Robinson Experimental Forest provides evidence of the inaccuracies. The Field Branch watershed and its three subcatchments (A, B, and C) have been gauged for flow since the early 1980s. At the weir location, Field Branch is mapped as a perennial stream, and in fact does have a measured flow duration of >90% of the time (Fig. 1). However, at the three flume locations, measured flow duration is classified as intermittent (<90% of the time) based on Hewlett (1982) (Fig. 1). At the "A" flume the map incorrectly classifies the stream as perennial, while at the "B" and "C" flumes the map incorrectly identifies the streams as ephemeral (Fig. 1). Based on the "blue line" method, a harvest occurring in the "A" subcatchment would require unneeded and costly BMPs while harvests occurring in the "B" and "C" subcatchments could potentially lead to elevated non-point source pollution because few BMPs would be applied. Others have also found the "blue line" method to be inaccurate,

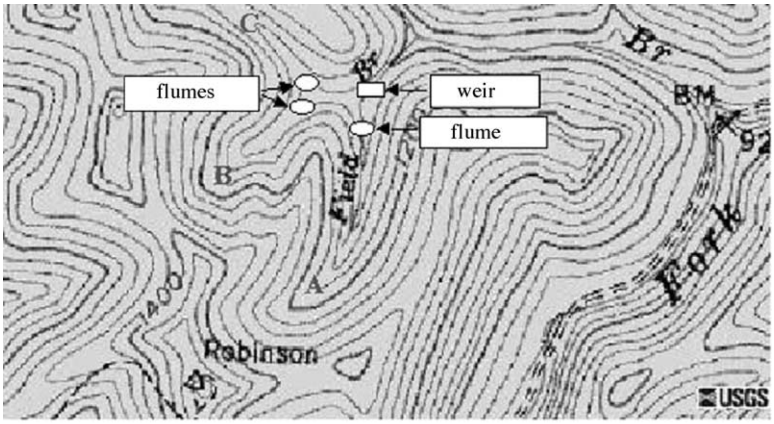

Fig. 1. USGS quadrangle map of the Field Branch watershed in the University of Kentucky's Robinson Forest. The USGS map correctly indicates perennial flow at the weir but incorrectly classifies flow at the three flumes located in the ABC subcatchments.

especially within the intermittent and ephemeral flow categories (Paybins, 2003).

An alternative to the ''blue line'' method is to measure stream and watershed properties and develop predictive models related to stream flow duration (Osterkamp and Hedman, 1979). The Channel Geometry method of predictive modeling is based on an understanding of stream morphology and the landscape level processes that control the flow of water and sediment (Hedman, 1970; Hedman et al., 1972; Osterkamp and Hedman, 1979, 1982; Rosgen, 1996). Water flow should be predicable from the channel's morphology. The Channel Geometry method has been used to predict discharges and flood flows and other flow characteristics. No studies were found that applied the Channel Geometry method to predict flow duration; however, the ability to predict flow duration would be highly useful for the proper application of forestry BMPs.

Few have investigated Channel Geometry relationships for intermittent and/or ephemeral channels and no relevant research has been conducted in the eastern US (Wharton, 1995). Previous studies on intermittent and ephemeral channels conducted in the western US have related discharge directly to channel width (Omang et al., 1983; Osterkamp and Hedman, 1979). And, while previous approaches have shown to be reasonably accurate in estimating perennial flows within ±30–40%, ephemeral flow errors are as high as 104%, while results for intermittent streams were not reported (Osterkamp and Hedman, 1979). Although ephemeral and intermittent flows appear to be more difficult to predict, it is likely that the lack of relevant data hinders these relationships.

In this study, the presence and duration of flow, not the magnitude, was characterized. We hypothesized that the presence and duration of flow would be significantly related to stream physical properties and would yield better relationships than those obtained previously for discharge. The objective of this study was to investigate these predictive relationships between flow duration and channel morphology for representative channels in Eastern Kentucky, and narrow the range of possible predictors. The ultimate goal is to provide forest managers and operators easily measurable parameters for determining flow duration so BMPs can be more effectively applied, reducing non-point source pollution, and lessening the economic impact of inaccurately defining stream class.

2. Site selection, design and methods

2.1. Climate

The Eastern Coalfield Region of Kentucky generally receives 100–125 cm of precipitation annually and has a mean annual air temperature of about 12 °C (Owenby et al., 2001). According to climate data collected at centrally located Jackson, KY during this study, the annual precipitation was 119 and 87 cm for the years 2000 and 2001, respectively, with the mean annual air temperature of 13 and 14 °C for the years 2000 and 2001, respectively (U.K. Ag. Weather Center, 2002). Precipitation in 2000 was within the normal averages but precipitation in 2001 was considerably lower than average. Temperatures were slightly higher than normal for both years. For 2002, the cumulative precipitation and the average monthly temperature through August were similar to those of 2000.

2.2. Research sites

Stream sites with a range of expected flow durations were chosen throughout the Eastern Coalfield Physiographic Region of Eastern Kentucky. Ten initial sites were selected. One site was in the Kentucky State Nature Preserves Commission's Blanton Forest in coordination with an ongoing project. Nine sites were selected in the Daniel Boone National Forest by consulting USGS 7.5 min Quadrangle topographic maps that fell within the boundaries of the National Forest (Fig. 2). Over 100 stream sites were specified in each stream category (i.e. ephemeral, intermittent, or perennial) with between five and seven randomly chosen sites picked from each category for field visits. Site selection was based on remoteness (avoidance of vandalism), access (ability to travel to sites through public land), terrain (negotiable hill slopes and clear stream reaches for measurement), and drainage (one site should not influence the amount of water passing another site). Stream site selections were completed during summer 2000 and stage height recording equipment was installed by 22 August, 2000 (Table 1).

As of May 2001 only eight of the nine sites installed in the Daniel Boone National Forest were still operational. The Orchard Branch site was abandoned due to unstable streambed conditions, which resulted in repeated dislodging of the stage height recorder. The remaining eight sites in the Daniel Boone National Forest and the Blanton Forest site had been monitored and the flow durations were calculated ($n = 9$). After 8 months no acceptable relationship was found between flow duration and stream parameters. To better detect possible relationships between flow duration and stream parameters, additional sites were added and the period of the study lengthened. Using the same consideration criteria for stream site selection, two sites from the original categorized lists of stream sites (Dog Branch and Marsh Branch) were entered into the study. These sites were installed on July 23, 2001 (Table 1).

Locations for the eleven region wide sites range from near Morehead, KY in the north, to Somerset in the south, and Blanton Forest in the southeast (Fig. 2). The ''blue line'' mapped classification of the eleven sites chosen was five ephemeral, five intermittent, and one perennial (Table 1). Sites were distributed across Eastern Kentucky to capture the effects of flow

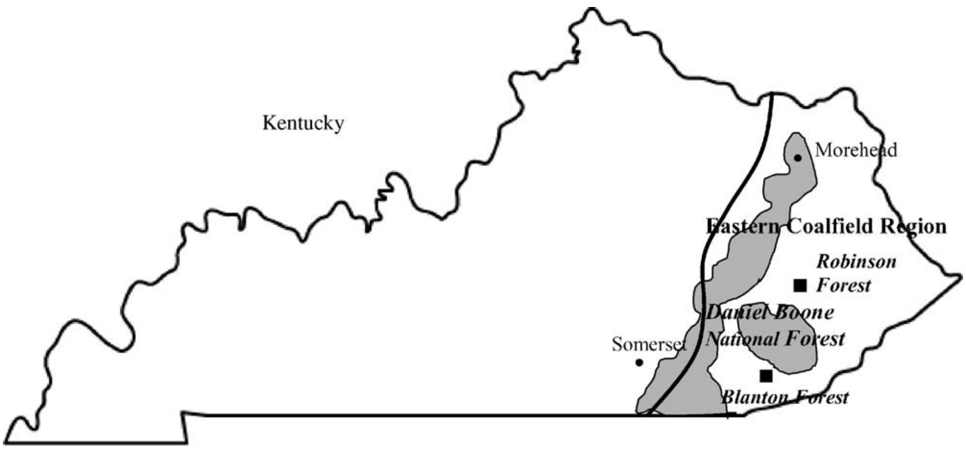

Fig. 2. Streams selected for study were within Eastern Coalfield Region (outlined in bold) in Eastern Kentucky. Study sites were located in the Daniel Boone National Forest (shaded), Blanton Forest and Robinson Forest.

Table 1
Stream site installation date, USGS stream class designation, measured flow duration from the 13-month data set, and occurrence of disturbance near to the site

Site Name	Date of well installation	USGS stream class designation	Measured flow duration (%)	Occurrence of disturbance
Region wide				
Road branch	8/21/00	Ephemeral	58.43	100 m from forest road
Pine creek	7/20/00	Ephemeral	84.80	75 m from forest road
Dog branch	6/23/01	Ephemeral	59.24	100 m from forest road
Marsh branch	6/23/01	Ephemeral	71.83	25 m from state hwy. 192
Watts creek	12/4/99	Ephemeral	78.57	Logging site upstream
Charity branch	8/21/00	Intermittent	96.47	Near old homestead site
South fork KY	8/20/00	Intermittent	98.50	None
Walnut creek	7/21/00	Intermittent	99.44	ORV trail nearby
Grassy branch	7/20/00	Intermittent	69.44	None
Lick fork	8/22/00	Intermittent	78.55	None
Scott creek	8/14/00	Perennial	99.35	None
Robinson forest				
"B"	Long-term	Ephemeral	86.42	BMP logging in 1982
"C"	Long-term	Ephemeral	98.77	Unrestricted logging 1982
Mulberry branch	7/23/01	Ephemeral	66.85	None
Tome branch	7/23/01	Ephemeral	61.48	None
Pine hollow	7/23/01	Ephemeral	64.48	None
LMS ephemeral	7/23/01	Ephemeral	58.54	None
Clem. eph 1	7/23/01	Ephemeral	53.20	None
Clem. eph 2	7/23/01	Ephemeral	57.53	None
"A"	Long-term	Perennial	77.97	None
Falling rock	Long-term	Perennial	92.35	None
Little mill seat	Long-term	Perennial	93.58	None
Clemons fork	Long-term	Perennial	99.26	None

duration on stream and watershed parameters throughout the entire region.

Considering that variation within a physiographic region may be significant when defining flow duration relationships, 12 additional sites were selected in the University of Kentucky's Robinson Experimental Forest (Robinson Forest) located east and north of the Daniel Boone National Forest (Fig. 2). Several streams in Robinson Forest are monitored with weirs or flumes with continuous stage height recorders. Four long-term sites were operational on 22 August, 2000 while two more were brought back on-line by July 23, 2001. Six previously unmonitored sites were also selected at Robinson Forest and installed by July 23, 2001. Sites were chosen within the 1409 ha Clemons Fork watershed that comprises approximately half of Robinson Forest. The landscape characteristics of Robinson Forest have been well described (Arthur et al., 1998). The Robinson Forest sites were chosen to represent a range of flow durations. The mapped classification of the Robinson Forest stream sites was eight ephemeral and four perennial streams (Table 1).

Timing of site installation allowed for both a 24- and a 13-month data set (Table 2). The 24-month data set began on 22 August, 2000. Eight initial sites in the Daniel Boone National Forest and the Blanton Forest site were installed by this time, and four of the long-term gauging sites in Robinson Forest were operational ($n = 13$). The 13-month data set includes the flow duration data beginning July 23, 2001 from all the sites in the 24-month data set as well as the two additional sites in the Daniel Boone National Forest, the six remotely gauged sites in Robinson Forest, and the two additional long-term gauging stations at Robinson Forest ($n = 23$). Both 13- and 24-month data sets combine randomly selected sites and predetermined chosen sites. The resulting data are therefore not random. Since the 13-month data set begins in July and ends in August, the data slightly over represent summer low flow conditions. Stream and watershed

Table 2
Flow duration and measured parameters for the 24-month data set and the 13-month data set (nd = no data)

Site name	13-Month flow duration (% time)	24-Month flow duration (% time)	Drainage area (ha)	Bankfull width (m)	Mean bankfull depth (m)	Width: depth ratio	Sinuosity (mm^{-1})	Stream slope (%)	Flood prone width (m)	Upland hillslope (%)	Depth to bedrock (cm)	Entrenchment ratio	Cross-sectional area (m^2)
Region Wide													
Road branch	58.4	58.2	8.5	2.50	0.11	21.8	1.04	13.0	8.7	12.5	40.6	3.5	0.29
Pine creek	84.8	90.0	8.5	1.65	0.09	17.7	1.02	5.0	2.8	9.0	40.6	1.7	0.15
Dog branch	59.2	nd	5.2	0.95	0.08	11.5	1.00	20.0	1.5	32.5	20.3	1.6	0.08
Marsh branch	71.8	nd	9.3	0.75	0.05	14.1	1.09	2.0	3.5	11.5	40.6	4.7	0.04
Watts creek	78.6	89.3	8.6	1.32	0.33	4.1	1.10	5.0	2.9	26.0	40.6	2.2	0.43
Charity branch	96.5	75.9	13.0	0.60	0.08	7.7	1.08	14.0	1.0	25.0	25.4	1.7	0.05
South fork KY	98.5	95.2	28.2 69.79	2.50	0.24	10.3	1.00	6.0	3.1	20.0	7.6	1.2	0.61
Walnut creek	99.4	95.5	61.7	1.70	0.07	25.5	1.02	4.0	2.8	18.3	15.2	1.6	0.11
Grassy branch	69.4	83.6	10.4	3.23	0.24	13.7	1.00	1.5	3.8	12.5	40.6	1.2	0.76
Lick fork	78.6	65.4	21.9	1.90	0.22	8.7	1.03	11.0	6.1	17.5	40.6	3.2	0.41
Scott creek	99.4	95.3	167.6	6.90	0.32	21.8	1.06	1.0	22.0	25.5	15.2	3.2	2.19
Robinson forest													
"B"	86.4	nd	11.0	2.60	0.23	11.4	1.03	9.0	5.0	66.0	0.0	1.9	0.59
"C"	88.8	nd	16.3	1.25	0.16	7.9	1.01	7.0	2.3	59.0	0.0	1.8	0.20
Mullberry branch	66.9	nd	3.3	0.50	0.07	6.9	1.03	20.0	1.0	45.0	40.6	1.9	0.04
Tome branch	61.5	nd	3.4	1.70	0.09	19.2	1.01	13.0	2.3	72.5	27.9	1.4	0.15
Pine hollow	64.5	nd	2.6	1.10	0.08	13.4	1.04	10.0	1.5	80.0	7.6	1.3	0.09
LMS Int.	58.5	nd	1.8	1.10	0.07	15.3	1.01	22.0	1.5	50.0	25.4	1.3	0.08
Unnamed 1	53.2	nd	1.0	0.60	0.09	6.5	1.00	23.0	1.0	40.0	33.0	1.7	0.06
Unnamed 2	57.5	nd	1.2	0.80	0.07	12.0	1.04	24.0	1.0	65.0	5.0	1.3	0.05
"A"	78.0	87.4	10.7	1.40	0.22	6.5	1.01	3.0	2.8	62.5	0.0	2.0	0.30
Falling rock	92.4	95.8	87.6	4.20	0.16	26.8	1.05	2.0	5.2	49.0	0.0	1.2	0.66
Little mill seat	93.6	98.9	79.4	3.40	0.16	20.7	1.00	3.0	7.0	48.5	0.0	2.1	0.56
Clemons fork	99.3	99.6	1409	11.20	0.37	30.3	1.00	1.0	17.1	13.5	0.0	1.5	4.14

parameters were measured during site installation (Table 2).

2.3. Parameter measurements

Flow duration was derived from stream stage height. Semi-continuous stage height recording wells were installed at all channel sites without an existing weir or flume. Wells were placed upright in the deepest part of the channel, secured with rebar, and programmed to measure stage height six times daily (i.e. every 4 h). Stage height was converted to flow duration by calculating a percentage of recordings representing flow. It was determined by observation that a stage height greater than 0.25 cm represented a flow condition for sites with recording wells (i.e. at >0.25 cm water was flowing and not just sitting in stagnant pools). Diurnal fluctuation in flows were commonly observed during low flow summer periods indicating that recording wells were allowing flow through the well casing and not trapping water. For the weir and flume sites at Robinson Forest, stage height recording charts were examined and field observations were made that indicated periods of no flow despite recorded stage heights. It was determined that stage heights corresponding with no stream flow for each weir or flume were between 0.6 and 2.1 cm.

Stream physical parameters measured or calculated for each site included bankfull width, mean bankfull depth, width:depth ratio, flood prone width, streambed slope, sinuosity, depth to bedrock, entrenchment ratio, and cross-sectional area (Rosgen, 1996). Bankfull stage was identified using field indicators such as change in vegetation, abrupt change in bank slope, presence of the floodplain, and evidence of erosive flow on bank soil (Rosgen, 1996; Wharton, 1995). Stream measurements were made using field techniques that would commonly be employed during timber harvest scouting and walk-through procedures rather than more rigorous surveying techniques that have been described (Harrelson et al., 1994). Because one of the objectives of this study was to develop easily measurable parameters that forest operators can use to define stream classification in Eastern Kentucky, using measurement techniques similar to those used commonly by forest operators was deemed appropriate for the study.

Equipment used for stream parameter measurements included a 50-m measuring tape, meter stick, a clinometer with a percent scale, and a rebar stake marked in centimeters. Width and depth were measured by securing a 50-m tape across the channel with pins. Depth measurements were taken at four to six locations, depending on stream width, at each cross-section. The flood prone width is defined as the width of the stream valley at twice the greatest bankfull depth (Rosgen, 1996). Stream slope percent was measured over a length of 30 m. Sinuosity was also measured over a 30-m distance, and is the ratio of channel length to valley length (Rosgen, 1996). Depth to bedrock was measured in centimeters by driving a marked stake through alluvial deposits to the bedrock. Choice of equipment limited depth to bedrock measurement to 40.6 cm. For the weir and flume sites in Robinson forest, depth to bedrock was zero because the gauging equipment was installed on bedrock. Entrenchment ratio was calculated as the flood prone width divided by the bankfull width (Rosgen, 1996). Cross-sectional area was calculated as the product of bankfull width and depth.

Watershed parameters included drainage area (ha) and hillslope (%). Drainage area was measured using a planimeter and USGS topographic quad maps. Hillslope (%) was the mean of slope readings measured from the streambed to approximately 30 m upslope, ninety degrees to the direction flow on both uplands. Occurrence of nearby, major disturbance was noted for each site (Table 1).

2.4. Regression analyses

Regression models were developed to determine the parameters that had the greatest importance for predicting flow duration. Single and multiple regression analyses were used on linear, and natural log transforms of the channel and watershed physical parameters to find the best relationship between these parameters and flow duration for the channels in the study. Regression analysis was performed on the 24- and 13-month data sets as well as separately for the Region Wide (i.e. Daniel Boone National Forest and Blanton Forest) and the Robinson Forest subsets using SAS (SAS Institute Inc., 1996).

r^2 selection models were run on the 24- and 13-month data sets with all channel and watershed parameters and their natural log transforms. This method of model selection finds the models with the maximum r^2 values beginning with individual parameters and increasing the number of parameters included until all parameters are considered in a ''full model'' (Freund and Wilson, 1998; SAS Institute Inc., 1996). These models indicated that, generally, the linear parameters entered the models before their natural log counterparts and are, therefore, better predictors of flow duration. The exceptions to this were watershed drainage area, flood prone width, and cross-sectional area, which generally entered first as natural log transforms.

r^2 selection was again used with only 11 channel and watershed parameters: width, depth, width:depth ratio, the natural log of flood prone width (floodLN), stream slope, sinuosity, depth to bedrock, entrenchment ratio, the natural log of cross-sectional area (cross-sectionLN), the natural log of watershed area (areaLN), and hillslope slope. Extreme variance inflation factors between variables indicated that floodLN and cross-sectionLN were causing a high rate of multicollinearity in the models and should be removed from the analysis.

With nine remaining variables, r^2 selection was again used to find the ''best'' models for the 24- and 13-month data sets and subsets. Mallows $C(p)$ statistic was reported in the SAS output (Freund and Wilson, 1998; SAS Institute Inc., 1996). Mallows $C(p)$ statistic compares the total squared error of a partial model to the full model to identify specification error (Freund and Wilson, 1998). Specification refers to the number of parameters in a given model; an over-specified model contains too many variables and these additional parameters fail to add to the model's fit and effectiveness (Freund and Wilson, 1998). The Mallows $C(p)$ value calculated for each model is compared to the number of parameters in the model plus one $(p + 1)$ (Freund and Wilson, 1998). Models with values less than $(p + 1)$ are considered over-specified (Freund and Wilson, 1998). A model that is slightly over-specified is considered a better model than a slightly under-specified model (Freund and Wilson, 1998). Model and parameter significance values, variance inflation factors, residuals, normality of error, correlation matrices, and presence of influential outliers were examined for each of the ''best'' models to verify assumptions regarding error.

3. Results

USGS mapped classification of each site was compared with measured flow duration using a definition of perennial >90%, ephemeral <10%, and intermittent flow duration between 90 and 10% (Hedman and Osterkamp, 1982; Hewlett, 1982). Mapped versus measured classifications were in agreement for six of the 23 stream sites from the 13-month data set for a success rate of just over 25%, illustrating the difficulty of defining flow duration for site-specific applications from topographic maps (Table 1).

Regression models were developed for the 24- and 13-month data sets and three data subsets in this study (Table 3). All of the selected ''best'' models had p-values for the F-test for overall fit with $p \leq 0.01$, and no parameter had a t-statistic (for testing significance of individual parameters) with a p-value greater than $p = 0.15$ (Table 3). Variance inflation factors were well below the usual threshold value of 10 indicating little multicollinearity (Freund and Wilson, 1998). Examination of residuals, studentized residual plots, and residual normality plots indicated all assumptions about error were held, and no influential outliers were detected (Freund and Wilson, 1998; SAS Institute, 1996).

The 24-month data set, starting August 2000, yielded a ''best'' model with the parameters areaLN, depth, width:depth ratio, and stream slope, which accounted for 85% of the variability in flow duration (Table 3). This model was the least under-specified of the four-variable models for this data set with $C(p) = 5.17$. The least over-specified model with four variables used the parameters width, stream slope, hillslope, and depth to bedrock. However, when similar three and five-variable models using hillslope slope were examined, the parameter hillslope slope was not highly significant. Therefore, the least under-specified model listed above was chosen. Stream slope, in a single regression, accounted for 69% of the variability in flow duration, followed by depth to bedrock ($r^2 = 0.46$), entrenchment ratio ($r^2 = 0.37$) and areaLN ($r^2 = 0.34$). All the single-variable models were under-specified. Addition of variables to the ''best'' model increased the r^2 values, however, all the five variable models were over-specified according to the $C(p)$ statistic. All three-variable models were under-specified.

Table 3
Model results including r^2, model parameters, and parameter coefficients and p-values for each data set

Data set	r^2	Model parameters	Coefficient	p-value
24-Month data set				
$n = 13$	0.85	Intercept	101.63	0.00
		AreaLN	8.16	0.02
		Depth	−68.06	0.05
		Width:depth ratio	−0.94	0.05
		Stream slope	−2.68	0.00
Region wide	0.91	Intercept	123.09	0.00
$n = 9$		Width	−3.02	0.06
		Stream slope	−2.58	0.00
		Depth to bedrock	−0.51	0.02
13-Month data set				
$n = 23$	0.85	Intercept	52.33	0.00
		AreaLN	19.63	0.00
		Width	−4.18	0.00
		Width:depth ratio	−0.52	0.09
		Entrenchment ratio	−3.68	0.05
Region wide	0.78	Intercept	37.04	0.02
$n = 11$		AreaLN	20.76	0.00
		Sinuosity	−4.47	0.09
		Entrenchment ratio	−4.00	0.15
Robinson forest	0.91	Intercept	45.18	0.00
$n = 12$		AreaLN	18.57	0.00
		Width	−4.96	0.01
Full data set				
$n = 23$	0.87	Intercept	92.92	0.00
		AreaLN	6.70	0.00
		Width:depth ratio	−0.62	0.03
		Stream slope	−1.30	0.00
		Entrenchment ratio	−5.29	0.01

All models had an F-test for overall fit with a p-value <0.01.

When the 24-month data set was restricted to the Region Wide sites ($n = 9$), the "best" model accounted for 91% of the variability in flow duration with three parameters including width, stream slope, and depth to bedrock (Table 3). The SAS software was unable to compute $C(p)$ values for this data set because the full model containing all nine variables was not "full rank." A model is not full rank when one or more tested independent variables are a linear combination of other variables (SAS Institute Inc., 1996). As a result, there is no measure of specification for the model from this data set. The three-variable model selected above had the highest r^2 and adjusted r^2 values of the three-variable models. The "best" model with four variables accounted for 95% of the variability in flow duration with adjusted $r^2 = 0.89$, using the variables width, sinuosity, stream slope, and depth to bedrock. The p-values of the t-test for the intercept and sinuosity parameters were not significant ($p = 0.42$ and 0.17, respectively), and the F-test for overall fit of the model was less significant than the three-variable model. Single-variable models that best accounted for flow duration were stream slope ($r^2 = 0.64$), depth to bedrock ($r^2 = 0.37$) and entrenchment ratio ($r^2 = 0.33$).

The 13-month data set, starting July 2001, produced a model with four parameters and accounted for 85% of the variability in flow duration (Table 3). The parameters in this model were areaLN, width, width:depth ratio, and entrenchment ratio. For this model $C(p) = 3.64$, which is slightly over-specified. However, any other four-variable models with less over-specification had parameters that were not highly significant and adjusted r^2 values less than the "best" model for this data set. All three-variable models were under-specified, and all five-variable models over-specified. The single variable models that best accounted for flow duration were areaLN ($r^2 = 0.66$), stream slope ($r^2 = 0.50$), and depth ($r^2 = 0.25$).

The data for the Region Wide sites for the 13-month data set ($n = 11$) resulted in a model accounting for 78% of the variability in flow duration with three parameters; areaLN, width, and entrenchment ratio (Table 3). This model was the least over-specified three-variable model ($C(p) = 2.99$), and all the parameters were found to be significant. All two-variable models were under-specified. The best two-variable model had the parameters areaLN ($p = 0.003$) and width ($p = 0.09$); however the r^2 for this model was only 0.70. All four-variable models were over-specified. All single-variable models were under-specified. The best three single-variable models were areaLN ($r^2 = 0.56$), depth to bedrock ($r^2 = 0.38$) and stream slope ($r^2 = 0.17$).

When the data from the Robinson Forest sites were modeled for 13 months ($n = 12$), 91% of the variability in flow duration was accounted for with only two parameters; areaLN ($p = 0.0001$) and width ($p = 0.01$) (Table 3). This model was the only over-specified of the two variable models ($C(p) = 0.48$). The least over-specified three-variable model used the parameters areaLN ($p = 0.0006$), width ($p = 0.03$), and entrenchment ratio ($p = 0.72$). Because all three-variable models were over-specified and entrenchment ratio was not highly significant, the two-variable model was chosen. Single-variable models such as areaLN ($r^2 = 0.77$), stream slope ($r^2 = 0.75$), and depth ($r^2 = 0.58$) were all under-specified. Analysis was not considered reliable for the Robinson Forest data from the 24-month data set due to small sample size ($n = 4$).

In addition to the regression models above, a ''full'' model was also produced to help identify the most important predictive variables for the Region. Sites with only 13-month data sets were combined with sites with 24-month data sets. The ''best'' model produced was a four-variable model using the parameters areaLN, width:depth ratio, stream slope, and entrenchment ratio to predict flow duration (Table 3, $r^2 = 0.87$). Other four- and five-variable models that were nearer specification according to Mallow's $C(p)$ had lower adjusted r^2 values. The best single parameter models were stream slope ($r^2 = 0.70$), areaLN ($r^2 = 0.62$) and depth ($r^2 = 0.41$).

To assess the fit of the ''full'' model, the parameters from all sites and all time periods ($n = 23$) were used to predict flow duration and compared to measured values (Fig. 3a) and standard residuals (Fig. 3b). The predicted flow groups well around the 1:1 line and, with one exception (Grassy Branch, see later discussion), the standard residuals are within two standard deviations of expected values and normally distributed about the line. These results indicate that we were able to successfully

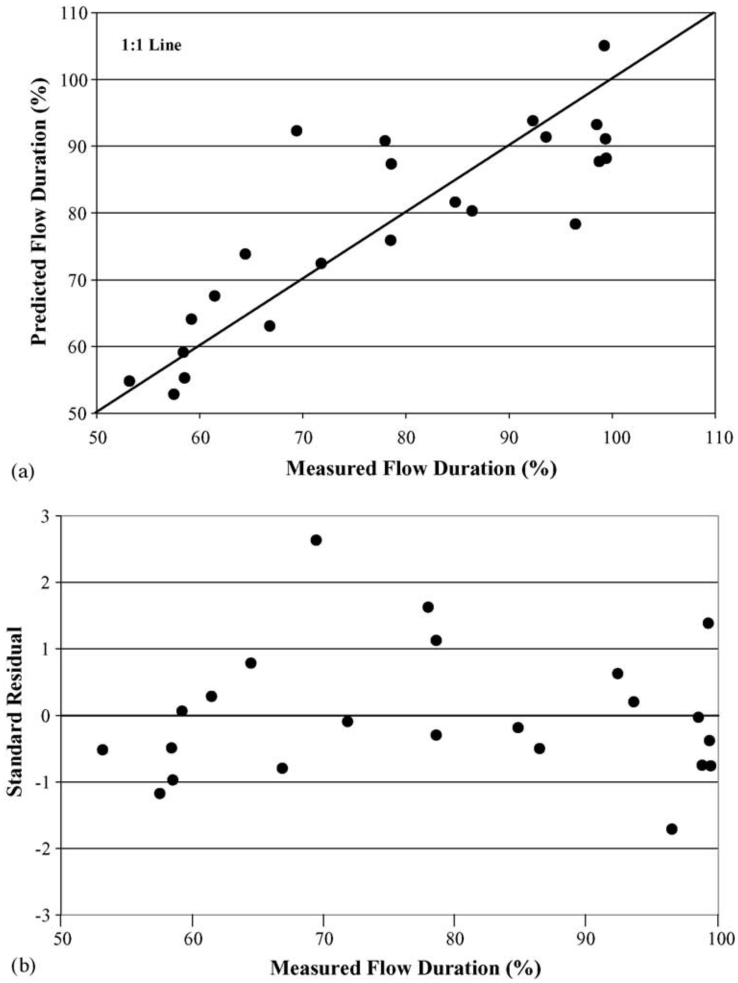

Fig. 3. Predicted vs. observed flow duration (a) and a standard residual plot using the entire data set and the full data set regression equation (b).

model the channels region wide and that our predictions were reasonably reliable.

4. Discussion

Commonly 10 years or more of hydrologic data are required to arrive at sound predictions of parameters such as flow return intervals. We understand that the time constraints imposed by this study will limit the predictability of determining long-term flow duration. However, based on the results, we are confident that the channel geometry method has merit and our results are applicable to the Eastern Coalfield Region of Kentucky. As hypothesized, the channel geometry method resulted in useful and significant relationships between flow duration and stream and watershed physical parameters. The natural log of watershed area, stream slope, bankfull width, width:depth ratio, and entrenchment ratio were important predictors of flow duration, appearing in two or more of the models produced from the data in this study. The parameters in the regression models from this study indicate functional stream dynamics at work in forming streams within this region (Rosgen, 1996). Similar logistic regression techniques were successful in predicting the probability that a stream was perennial in Massachusetts; however, only basin level properties derived from digital elevation models and digital maps were used in the analysis (Bent and Archfield, 2002). As in this study, drainage area was an important predictor of flow duration but also drainage density, mean basin slope, area of stratified drift deposits and location in the state were useful in their predictions. The authors indicated the measurement of stream channel physical properties (Channel Geometry Method) could improve their model predictability (Bent and Archfield, 2002).

Relationships between stream flow characteristics and channel and watershed parameters are expected to vary across the boundaries of physiographic regions. Differences in geology, landform, climate, and other factors create a high variation in channel and watershed parameters. Relationships developed in this study will likely be less applicable or invalid outside the region. Even within a physiographic region, site-level factors appear to also be important. For example, the sites within 1409 ha Clemons Fork watershed in Robinson Forest matched the best prediction of flow duration despite only being analyzed for a 13-month period (Table 3). In the Pacific Northwest, bankfull discharge return intervals were linked to ecoregional and vegetation factors more precisely than an average value predicted for the entire region (Castro and Jackson, 2001). Additionally, bankfull discharge was better accounted for using regression equations within the smaller ecoregions than across the entire Pacific Northwest (Castro and Jackson, 2001). The results of this Eastern Kentucky study along with the Pacific Northwest study suggest local variation within a physiographic region is important in predicting stream flow duration. Additional studies may indicate that subregions are required for the accurate prediction of flow duration.

Additional parameters that have been used to predict flow characteristics and may also be useful to predict flow duration include meander:width ratio, riffle:pool ratio, and wetted perimeter (Rosgen, 1996; Mackey et al., 1998). In addition, measurement of the diurnal fluctuation in streambed temperature was highly successful at predicting stream flow and duration in the southwestern US in ephemeral channels and should be investigated elsewhere (Constantz et al., 2001). Study of biological factors, such as stream macroinvertebrates, may also be helpful to predict flow duration because species habitat requirements will determine their presence in streams that flow within some threshold of duration (Federal Interagency Stream Restoration Working Group, 1998).

Unfortunately, based on our definition, we did not sample any truly ephemeral channels in our study. Although the USGS blue line maps indicated that 13 of our 23 sites should have been ephemeral, our lowest flow duration was over 50% which is much higher than the $<10\%$ definition we are using in this study. Our models appear robust for channels with $>50\%$ flow duration but should be questioned for channels with $<50\%$ flow duration. Given the limits imposed by our selection of sites, we used the "full" model to determine reasonable values for defining perennial and intermittent channels based on the watershed or catchment size (Table 4). We extended the model where appropriate to also predict parameters for ephemeral channels realizing that these predicted values are untested and may be outside the range of predictability for the model. Given our model results

Table 4
General guideline recommendations to classify stream channels based on the full data set model

Area (ha)	Width:depth	Slope (%)	Entrenchment ratio	Channel class
1.0–5.0	1–25	<30	<2	Intermittent
	>25	>30	>2	Ephemeral
5–10	1–3	1–2	<1.5	Perennial
	3–50	2–30	1.5–4	Intermittent
	>50	>30	>4	Ephemeral
10–25	1–6	1–3	<1.5	Perennial
	6–50+	3–30+	1.5–5+	Intermittent
25–100	1–30	1–10	<3	Perennial
	>30	10–30+	>3	Intermittent
100+	Any value	Any value	Any value	Perennial

and general recommendations, it is clear that as watershed size increases and width:depth ratio, stream slope, and entrenchment ratio decreases, the channel flow duration increases (Tables 3 and 4). From a stream morphology and hydrological point of view, none of these results are surprising. In this region, as streams approach the perennial class they become lower gradient and more incised or entrenched leading to lower stream slopes, width:depth ratios and entrenchment ratios. Based on the recommendations in Table 4, 22 of 23 or >95% of the streams in this study classify correctly based on our flow duration data. The only site that does not fit our recommendations is Grassy Branch, an intermittent stream. Grassy Branch has a width:depth ratio (13.7) characteristic of an intermittent channel but a stream slope (1.5) and entrenchment ratio (1.2) that are characteristic of a perennial channel (Table 4).

5. Conclusions

Flow duration is commonly used to determine the appropriate forestry BMPs to apply in riparian areas. Generally, as flow duration increases the potential for non-point source pollution also increases and BMPs intensify to protect water quality. The current definitions for flow duration of stream classes are not standardized and often qualitative, making application of proper BMPs difficult. The common method for determining stream flow duration class is to use USGS Quadrangle ‘‘blue line’’ maps but we and others have shown this method to be inaccurate at the site level. An alternative to this method is to measure stream and watershed properties and develop predictive models for stream flow duration. We instrumented streams ranging from ephemeral to perennial, by the USGS designation, in the Eastern Coalfields Region of Eastern Kentucky and measured flow duration and stream and watershed parameters. Models showed that stream bankfull width, width:depth ratio, streambed slope, entrenchment ratio, depth to bedrock, and the natural log of watershed area are significantly related to stream flow duration.

Previous research using the channel geometry characteristics to predict flow duration was not found in the literature. While this study indicates that this method can be used successfully, future studies should focus on lengthening the duration of data collection, investigation of additional predictive parameters, validation of predictive ability, applying the method to lower flow systems and expansion of these principles to other physiographic regions. Long-term data collection for determining flow duration is important to account for the seasonal and annual variation in precipitation as it affects stream flow and flow duration. The models produced in this study were not applied or tested on additional data to validate their predictive ability. Although we attempted to include lower flow duration ephemeral channels in our study, in reality our sites did not even approach our selected definition for ephemeral flows. Also, the relationships found in this study are likely to be applicable only to the Eastern Coalfield physiographic region and possibly within smaller subregions. Additional research is needed to determine how portable the relationships found in this study are to other regions.

The goal of this research was to provide some easily measurable parameters to forest managers and operators to allow onsite stream flow duration classification, leading to improved application of forestry BMP guidelines addressing timber harvesting and other intensive forest operations near streams. Given the high predictive capability of our models, we believe that our recommendations in Table 4 are robust for the Eastern Coalfield Physiologic Region of Eastern Kentucky.

Acknowledgements

The authors would like to thank the University of Kentucky, the USDA Forest Service North Central Research Station and the Kentucky Water Resources Research Center for supporting this study. Also thank you to Kelly and Nathan Bolte, Peter Hadjiev, David Collett, Will Marshall and the rest of the staff at Robinson Forest for helping with this study.

References

Arthur, M.A., Coltharp, G.B., Brown, D.L., 1998. Effects of best management practices on forest streamwater quality in eastern Kentucky. J. Am. Water Resources Assoc. 34 (3), 481–495.

Bent, G.C., Archfield, S.A., 2002. A logistic regression equation for estimating the probability of a stream flowing perennially in Massachusetts. USGS Water-Resources Investigations Report 02-4043, 45 pp.

Castro, J.M., Jackson, P.L., 2001. Bankfull discharge recurrence intervals and regional hydraulic geometry relationships: patterns in the Pacific Northwest, USA. J. Am. Water Resources Assoc. 37 (5), 317–328.

Constantz, J., Stonestrom, D., Stewart, A.E., Niswonger, R., Smith, T.R., 2001. Analysis of streambed temperature in ephemeral channels to determine stream flow frequency and duration. Water Resources Res 37 (2), 317–328.

Federal Interagency Stream Restoration Working group, 1998. Stream Corridor Restoration: Principles, Processes, and Practices. US Government Printing Office. Washington DC.

Freund, R.J., Wilson, W.J., 1998. Regression Analysis: Statistical Modeling of a Response Variable. Academic Press, San Diego, CA, 444 pp.

Harrelson, C.C., Rawlins, C.L., Potyondy, J.P., 1994. Stream Channel Reference Sites: An Illustrated Guild to Field Technique. USDA Forest Service General Technical Report RM-245, 61 pp.

Hedman, E.R., Osterkamp, W.R., 1982. Stream flow characteristics related to channel geometry of streams in western United States. USGS Water-Supply Paper 2193, 17 pp.

Hedman, E.R., Moore, D.O., Livingston, R.K., 1972. Selected stream flow characteristics as related to channel geometry in Colorado. USGS open file report, 14 pp.

Hedman, E.R., 1970. Mean annual runoff as related to channel geometry of selected streams in California. USGS Water-Supply Paper 199-E, 17 pp.

Helms, J.A., 1998. The Dictionary of Forestry. The Society of American Foresters, Bethesda, MD, 210 pp.

Hewlett, J.D., 1982. Principles of Forest Hydrology. University of Georgia Press, Athens, Ga, 183 pp.

Mackey, P.C., Barlow, P.M., Ries, K.G., 1998. Relationships between discharge and wetted perimeter and other hydraulic-geometry characteristics at selected stream flow-gaging stations in Massachusetts. USGS Water-Resources Investigations Report 98-4094.

Nebraska Forest Service, University of Nebraska, 1998. Forestry Best Management Practices for Nebraska a Reference Guide for Loggers, Landowners and Managers. [monograph on the internet] The Service; [cited 11/02/2000] available from: http://www.ianr.unl.edu/pubs/forestry/nfs/nfs-1.htm#fip.

Omang, R.J., Parrett, C., Hull, J.A., 1983. Mean annual runoff and peakflow estimates based on channel geometry of streams in southeastern Montana. USGS Water Resources Investigations 82-4092, 53 pp.

Osterkamp, W.R., Hedman, E.R., 1982. Perennial stream flow characteristics related to channel geometry in the Missouri River Basin. USGS Profess. Paper 1242, 37 pp.

Osterkamp, W.R., Hedman, E.R., 1979. Discharge estimates in surface-mine areas using channel-geometry techniques. In: Proceedings of the Symposium on Surface Mining Hydrology, Sedimentology and Reclamation. U. of Kentucky, Lexington, KY, pp. 43–49.

Owenby, J., Heim, R. Jr., Burgin, M., Ezell, D., 2001. Climatography of the U.S. no. 81 - Supplement # 3 Maps of Annual 1961-1990 Normal Temperature, Precipitation and Degree Days. [online report]. National Climate Data Center. [updated 29-may-2001; cited 10-Dec-2002] Available from: http://lwf.ncdc.noaa.gov/oa/documentlibrary/clim81supp3/clim81.html.

Paybins, K.S., 2003. Flow origin, drainage area, and hydrologic characteristics for headwater streams in the mountaintop coal-mining region of southern West Virginia, 2000-01. USGS Water Resources Investigations Report, 02-4300. 20 pp.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology Books, Pagosa Springs, Colorado.

SAS Institute Inc., 1996. Release 6.12 SAS/STAT User's Guide. Cary NC.

Stringer, J., Thompson, A., 2000. Comparison of Forestry Best Management Practices: Part 1 Streamside Management Zones. Forest Landowner May/June 2000. Forest Landowners Association, Atlanta, GA, pp. 22–27.

Stringer, J, Perkins, C., 2001. Kentucky Forest Practice Guidelines for Water Quality Management. Univ. of KY. Coop. Ext. Serv., Dept. of For. FOR-67, 111 pp.

TFS, 2000. Texas Forest Service., 2000. Texas Forestry Best Management Practices. [monograph on the internet] the service; [cited 11/02/2000] available from: http://txforestservice.tamu.edu/forest_management/best_management_practices/pdf/BMP%20Handbook2000b.pdf.

University of Kentucky Agriculture Weather Center, 2002. [online database] Lexington, KY The University [cited 13-Dec-2002] Available from: http://wwwagwx.ca.uky.edu/.

Wharton, G., 1995. The channel geometry method: guidelines and applications. Earth Surf. Proc. Landforms 20, 649–660.