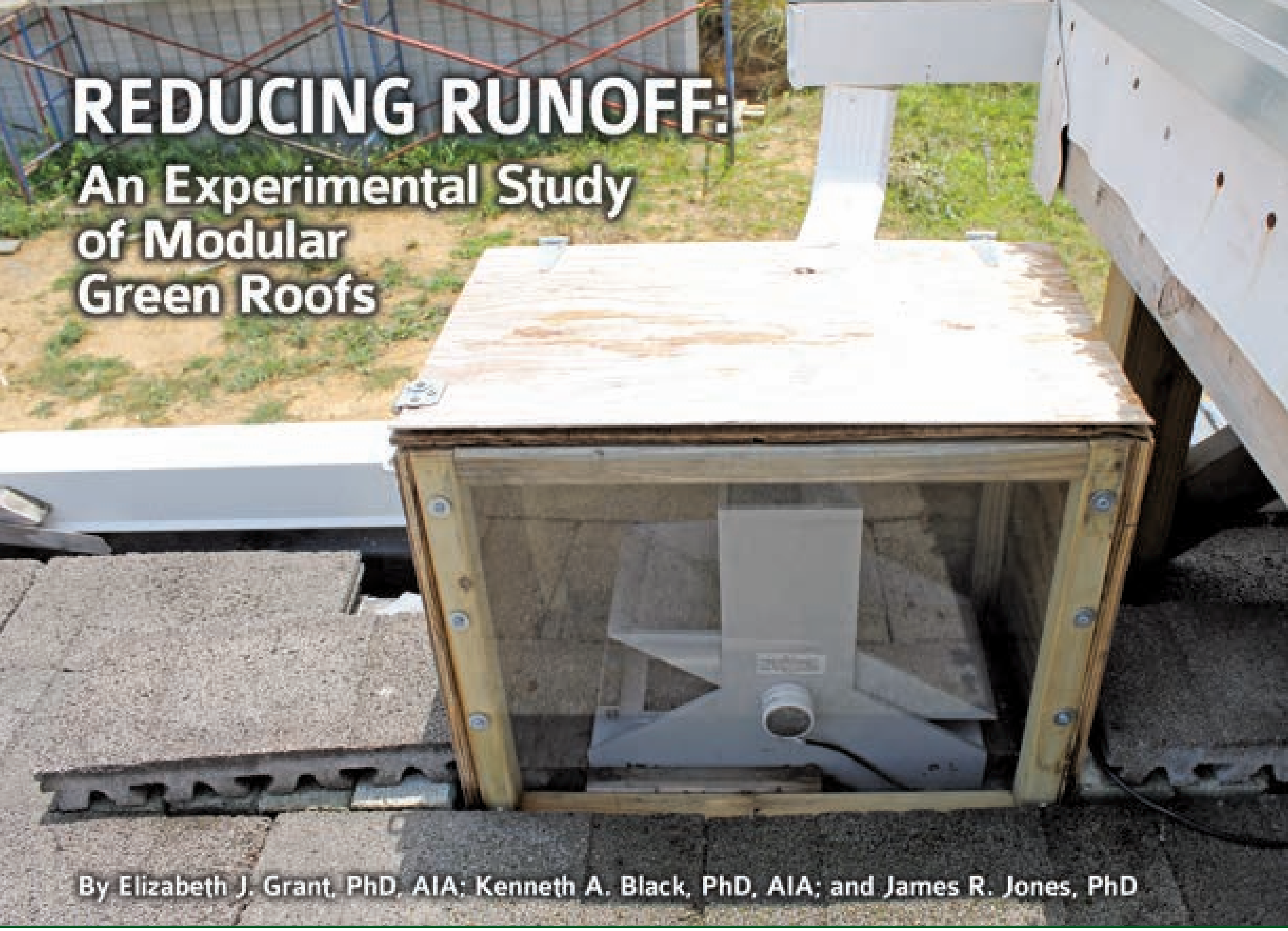
REDUCING RUNOFF: An Experimental Study of Modular Green Roofs



By Elizabeth J. Grant, PhD, AIA; Kenneth A. Black, PhD, AIA; and James R. Jones, PhD

Figure 1. Tipping bucket flow gauge in protective box.

Vegetated or "green" roofing has many well-established benefits. Chief among them is their capacity to reduce stormwater runoff in urban places where land is at a premium and little pervious ground surface remains. The often-overlooked roof surface can be transformed from a liability to an asset when covered with living plants. Through the process of evapotranspiration, defined as the combination of evaporation from soil and other surfaces and transpiration of water by plants, vegetated roofs reduce runoff volumes and flow rates from rainstorms, helping to prevent sewer overflows and stream bank erosion. This article presents a study to determine the efficacy of different depths of modular vegetated roofing systems in terms of reduction of runoff in low-slope conditions, and to relate this efficacy to a range of climatic variables.

BACKGROUND

Guidelines and Standards

When used in combination with other stormwater best-management practices, vegetated roofs can offer an amenity to city dwellers while also providing runoff reduction benefits. In an effort to quantify these benefits,the German landscape construction and development research organization Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) presented a table with percentages of annual water retention for vegetated roofs of various vegetation support course depths in the 2002 edition of the FLL *Guideline for the Planning, Execution, and Upkeep of Green-Roof Sites*.[1] FLL cautioned users of the table to adjust the values for local weather conditions and specific vegetated roof products used. The authors pointed to the depth of a substrate, not its makeup, as the most important factor in determining the volume of water a vegetated roof can retain.

In response to the surge in implementation of vegetated roof systems in Canada and the United States over the past 20 years, ASTM International subsequently developed a standard to assist vegetated roof designers, ASTM E2777-20, *Standard Guide for Vegetative (Green) Roof Systems*.[2] Although the standard does not provide coefficients linking substrate depth to runoff reduction, Section 7.3.2.4 addresses the water retention capacity of green roof systems as follows: "Water retention is an important requirement of the media and vegetative (green) roof system … Rainfall retention is generally improved with thicker media layers and water retention components."

Previous Research

The potential of vegetated roofs to reduce the volume of roof runoff is a topic of continuing interest and has been investigated by multiple researchers in North America. Several studies have documented increased runoff retention

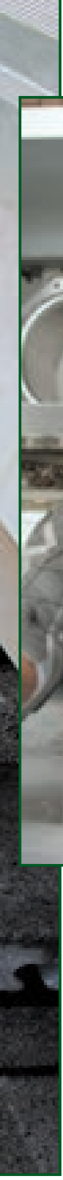


Figure 2. Draining edge detail.

using in situ experimental studies of low-slope vegetated roofs exposed to naturally occurring storm conditions.[3-17] A range of variables—including the depth of the growing medium; the slope of the roof; the type of vegetation; and the climate, storm intensity, and storm frequency at the roof site—have been found to contribute to a wide variety of outcomes. All of the vegetated roofs in these studies retained some percentage of annual runoff, ranging from 22% to 100%.

Stovin et al.[18] and Carson et al.[19] used simulation and regression models validated with experimental data to address climatic and seasonal variations in vegetated roof retention. In these studies, investigators observed an increase in runoff percentage from larger versus smaller storms, among other phenomena. Addressing both vegetated and nonvegetated roof modules, Volder and Dvorak[20] found that while storm event size was the most significant indicator of green roof runoff retention, volumetric water content of the growing medium also influenced performance, with wetter media retaining less runoff. Increased time between storms was a strong predictor of decreased volumetric water content.

Studies by Fassman-Beck et al.[21] and Carson et al.[19] emphasized the variability of vegetated roofs' performance based on rainfall patterns. For this reason, those authors stressed the need to focus on long-term performance of green roofs rather than relying on conclusions based on short-term study periods that may not reflect the typical rainfall patterns in an area over time. A larger body of research is needed to further understand vegetated roof systems' performance parameters.

Characteristics and Advantages of Green Roof Modules

A green roof module is defined in ASTM E2777-20 Section 3.2.21 as a "pre-manufactured unit containing some of the functional elements of a vegetative (green) roof system ... Independent modules are designed to be placed adjacent, and sometimes linked to one another, in order to cover roof surfaces." Modular vegetated systems are often favored when building owners require a fully vegetated roof system at the beginning of the project, rather than a system that requires an establishment phase of one to two years. Modular systems also offer the advantage of being easily removed and replaced upon the discovery of a roof leak or for other maintenance purposes.

METHODOLOGY

To determine the efficacy of different depths of modular vegetated roofing systems in terms of reduction of runoff in low-slope conditions and relate this efficacy to a range of climatic variables, a research team at the College of Architecture and Urban Studies at Virginia Tech conducted an experimental study atop the Test Cell Building at the Research and Demonstration Facility at the Blacksburg campus. Blacksburg is located in American Society of Heating, Refrigerating, and Air-Conditioning Engineers Climate Zone 4. (To view a Climate Zone map, visit https://basc.pnnl.gov/images/iecc-climate-zone-map.)

The project began with the erection of five plywood platforms, each measuring 2.4 × 2.4 m (8 × 8 ft), which were covered with a white thermoplastic polyolefin (TPO) single-ply roof membrane. The platforms were constructed with a 2% (¼:12) monoslope toward a gutter and were prepared for installation of the modular vegetated roof system with the placement of aluminum edge angles designed to divert all water incident on the platforms' surface to the draining edge. The draining edge was fitted with a similar aluminum angle perforated with slots to allow runoff to drain into a gutter, which was also sloped at 2% to a downspout. The downspout discharged into the hopper of tipping bucket flow gauges sized to be three times more sensitive than a standard tipping bucket rain gauge, while also being able to record runoff from a 100-year storm without being overwhelmed. The tipping buckets were located inside boxes to prevent additional rainfall or debris from entering their hoppers. The tipping bucket and drainage configuration are shown in **Fig. 1** and **2**.

Four of the test platforms were covered with interlocking modules of 100% recycled polypropylene with an average of 10% postconsumer and 90% postindustrial material, and 2.5-mm (0.1-in.)-thick walls; each module measured 0.3 × 0.6 m (1 × 2 ft). These modules had articulated bases with slots shaped to allow for rapid drainage of runoff with minimal loss of growing medium. They served as both drainage and filter layer for the green roof.

The modules were prefilled with growing medium composed of expanded slate aggregate produced by a rotary kiln process mixed with organic material and, at the three vegetated platforms, they were fully covered with a mix of seven sedum varieties that had been grown to maturity at the nursery before shipment to the experimental site. Students and representatives of the nursery supplying the modular vegetated roofing system installed the modules.

The four platforms covered with modules received specific treatments. Platform 1, the "deep" system, had 152 mm (6 in.) of growing medium; platforms 2 and 4, the "standard" and "standard medium only" systems, respectively, had 108 mm (4.25 in.) of growing medium; and platform 2, the "lite" system, had 64 mm (6.5 in.) of growing medium.

The vegetated deep, standard, and lite systems (platforms 1–3) were shipped to the

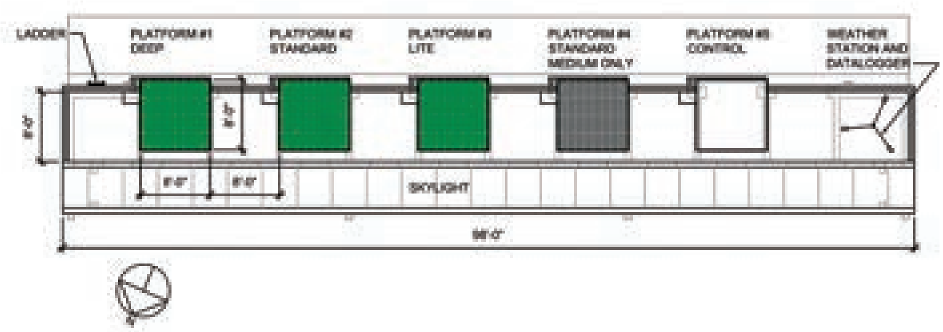


Figure 3. Experimental setup at the Test Cell Building at Virginia Tech's Research and Demonstration Facility.

experimental site on October 13, 2010, along with the standard medium only system (platform 4), which was left unplanted. The fifth platform was reserved as a control, with the white TPO left exposed. A weather station and data logger were affixed to a mast adjacent to the control platform. **Figure 3** illustrates the arrangement of platforms and the weather station on the roof of the Test Cell Building, and **Figure 4** is a photo of the test platforms with the deep system platform in the foreground.

The weather station and an adjacent tipping bucket rain gauge collected data on rainfall, temperature, relative humidity, wind speed, wind direction, and photosynthetically active radiation. **Table 1** details the instruments employed in the study. Campbell Scientific PC400 software was used to scan the measurement devices at 5-minute intervals across the study period, August 17, 2011, to October 30, 2012.

RESULTS

During the study period, 159 separate storm events occurred. If rainfall occurred within 6 hours of rainfall or runoff from a previous storm, the two events were counted as one storm event. Of these 159 storms, those with less than 1 mm (0.04 in.) of rainfall (n = 54) were excluded from analysis, as runoff volumes from these storms fell within the margin of error of the tipping bucket flow gauges. Of the remaining 105 storms, 29 were determined to have occurred during a period when the ambient temperature dropped below 0°C (32°F) at any point during the day the storm began through the day it ceased raining. These storms were excluded because the tipping bucket flow gauges may have been filled with freezing water during these periods and results were therefore unreliable. An additional two storms were removed from the data set as being outliers in bivariate scatterplots. The resulting 74 storms were grouped for analysis into the following three categories:

- Light storms—events with a total rainfall of at least 1 mm (0.04 in.) but less than 3 mm (0.12 in.) (n = 22)
- Medium storms—events with total rainfall of at least 3 mm (0.12 in.) but less than 7 mm (0.28 in.) (n = 16)
- Heavy storms—events with total rainfall of 7 mm (0.28 in.) or more (n = 36)

Figure 4. Test platforms atop the Test Cell Building.

Description	Manufacturer	Model
Data logger	Campbell Scientific	CR1000
Temperature/relative humidity probe	Vaisala	HMP50
Solar radiation sensor	LI-COR	LI190SB
Wind sentry set	RM Young	03002
Tipping bucket flow gauge	Hydrological Services	TB1L
Tipping bucket rain gauge	Hydrological Services	TB6

Table 1. Equipment used in modular vegetated roof study

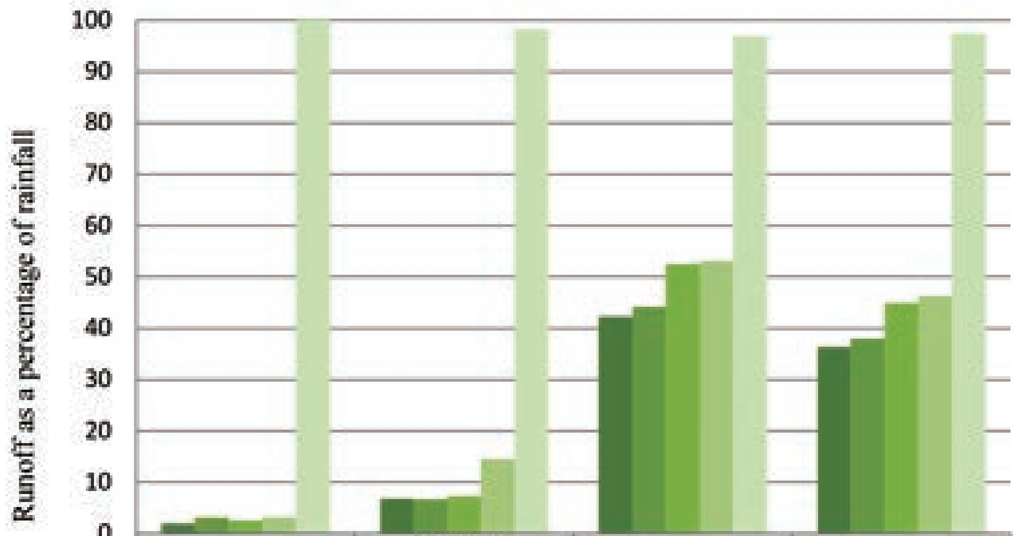
Figure 5 shows the aggregate runoff for each test platform as a percentage of rainfall during the test period. In storms between 1 and 3 mm (0.04 and 0.12 in.), the vegetated platforms as well as the platform containing only growing medium released a very small fraction of the incident rainfall. The aggregate runoff for these platforms increased as the size of the storm increased. In general, the platforms with increased depths of growing medium yielded a slight reduction in runoff compared with the platforms with shallower depths.

The standard vegetated platform retained somewhat more runoff than the standard medium only platform. All of the treatment platforms, including the standard medium only platform, retained significantly more runoff than the control platform. The runoff as a percentage of rainfall exceeded 100% for the control platform for light storms because the tipping bucket flow gauge at the control platform was three times more sensitive than the rain gauge.

The process of developing a predictive function to determine runoff in millimeters per square meter as a dependent variable for each of the test platforms began with 11 independent variables included in a multiple regression analysis. These variables were included as possible influencers based on analysis of a series of bivariate scatterplots. The independent variables initially included were as follows:

- Duration of the previous storm event in hours
- Mean intensity of the previous storm event in mm/hour (in./hour)
- Time since the previous storm event in days
- Duration of the present storm event in hours
- Intensity of the present storm event in mm/hour (in./hour)
- Mean temperature during the present storm event in °C (°F)
- Mean relative humidity during the present storm event in percentage
- Mean temperature between the previous and present storm events in °C (°F)
- Mean relative humidity between the previous and present storm events in percentage
- Mean photosynthetically active radiation between the previous and present storm events in watts per square meter (watts per square foot)
- Rainfall in mm (in.)

After a series of iterations to eliminate weak predictor variables (all the variables listed above that were not included in the regression equations in **Table 2**), the final regression functions included only those independent variables that had *t* values less than –2 or greater than 2. Table 2 presents the regression functions for the four test platforms and the control platform. **Table 3** shows the R^2, *t*, and *P* values for the five regression equations (see sidebar, "Regression Simplified").



	Light Storms	Medium Storms	Heavy Storms	Overall
Deep	1.9	6.8	42	36
Standard	3.2	6.6	44	38
Lite	2.6	7.3	52	45
Medium Only	3.2	14	53	46
Control	103	98	97	97

Figure 5. Runoff as a percentage of rainfall by storm classification.

Platform	Function
Deep	$y_{deep} = 1.6 - 0.33x_1 + 0.61x_2 + 3.2$
Standard	$y_{standard} = -1.8 - 0.28x_1 + 0.63x_2 + 2.8$
Lite	$y_{lite} = -2.1 - 0.28x_1 + 0.73x_2 + 2.7$
Standard medium only	$y_{medium\ only} = 1.4 - 0.33x_1 + 0.73x_2 - 0.18x_3 + 2.3$
Control	$y_{control} = 1.1 + 0.99x_2 - 0.067x_3 + 0.92$

Notes:

y is runoff per platform area in mm/m^2.

x_1 is time in days since the previous storm event.

x_2 is rainfall in mm.

x_3 is the mean temperature between the previous and present storm events in °C.

Since temperature in °C is an interval scale, these regression functions are appropriate for SI units only. Data in US Customary Units need to be converted to SI before using these equations.

Table 2. Regression functions for the four test platforms and the control platform

		Time since previous storm		Rainfall		Average temperature between events	
Platform	R^2	*t*	*P*	*t*	*P*	*t*	*P*
Deep	0.77	–2.1	0.041	16	<0.0001	N/A	N/A
Standard	0.83	–2.0	0.046	18	<0.0001	N/A	N/A
Lite	0.88	–2.1	0.036	22	<0.0001	N/A	N/A
Standard medium only	0.91	–2.9	0.0047	26	<0.0001	–3.1	0.0031
Control	0.99	N/A	N/A	88	<0.0001	–2.9	0.0054

Note: N/A = not applicable. See sidebar, "Regression Simplified," for simple definitions of R^2, *t*, and *P*.

Table 3. R^2*, t, and P values for the study's regression equations*

REGRESSION SIMPLIFIED

In simple terms, *t*-value is a statistical measurement that helps provide evidence that a variable *x* has a significant impact on the outcome *y*. The greater the *t*-value is (in absolute terms, either positive or negative), the stronger the evidence that this variable affects the outcome. *P*-value measures the probability (a value of 1 means 100% probability) that the outcome observed is **not** due to the effect of variable *x*. The lower the *P*-value is, the stronger the evidence that the variable *x* **does** affect the outcome *y*. R^2, or *R*-squared, is a measure of the proportion of variance in *y* that can be explained by the variance in *x* or multiple *x*'s. The larger the R^2 (out of 1), the better the "fit" of the model, that is, the more accurately the *x*'s predict the value of *y*.

CONCLUSIONS

Viewed together, the data demonstrate that platforms covered with modular vegetated roofing systems exhibited less runoff than a control platform covered only with a white reflective roof membrane. They also showed a pattern of decreasing runoff with increasing depths of the modular system. In other words, the deeper the system was, the more rainfall that was retained. The deep system retained 64% of the rainfall that fell on it, whereas the standard system retained 62%, the lite system retained 55%, the medium only system retained 54%, and the control roof retained only 3%, likely from evaporation.

The regression analysis resulsts suggest that runoff in millimeters per square meter was inversely related to the time in days since the previous storm event. This finding would seem to indicate that when two storms were closely spaced, runoff for the second storm was greater than if there had been a larger time span between the storms, most likely because the vegetation and growing medium may still have been damp from the previous storm. The statistical analysis also showed, unsurprisingly, that runoff was positively correlated with incident rainfall, and this correlation was stronger with shallower modular vegetated roof depths.

At the control platform, the amount of rainfall was a strong predictor of runoff. The average temperature between the previous and present storm events was inversely related to rainfall in the standard medium only and control platforms, showing that higher temperatures reduced runoff, perhaps due to increased rates of evaporation. However, this relationship did not prove statistically significant in any of the three vegetated platforms.

The equations generated from this study have predictive power for future installations. The results demonstrate the relative performance of different depths of modular vegetated roofing systems and their relationship to key climate variables. While funding and space limitations prevented replication of each treatment in this study, the findings could be strengthened with future repetition and refinement of the experiment. Doing so would broaden the range of data and further validate the equations derived from the current data set.

The ultimate goal of this research is to provide information useful to architects and other roof designers who are making decisions about incorporating modular vegetated roofs into their projects. By adding to the body of knowledge on the performance of these systems, studies such as this help designers gain confidence that they are identifying and understanding runoff and retention capabilities of different vegetated roof systems.

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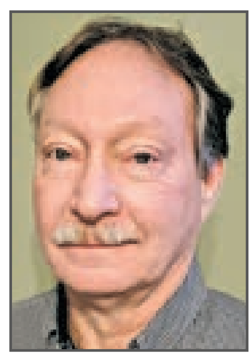

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