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IDEAS & INNOVATIONS

Calibrating the USLE P-factor using program FLUVIAL-12

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The Universal Soil Loss Equation (USLE) has been the underpinning of numerous research efforts in understanding and describing soil erosion. The USLE is referred to in several papers and books and is fundamental to advances in estimating and predicting soil loss and soil erosion. A complete literature review would include many publications but may begin with the work of Walter H. Wischmeier, resulting in a series of publications (Wischmeier and Smith 1962; Wischmeier 1972, 1976) that are typically referenced in numerous publications that deal with soil erosion topics today. The more recent methodologies, including Modified Universal Soil Loss Equation (MUSLE), Revised Universal Soil Loss Equation (RUSLE), and RUSLE2 (Foster and Highfill 1983; Laflen and Moldenhauer 2003; and Toy et al. 1999) are based on the USLE and include additional features that further analyze particular aspects of the soil erosion process.

In the current paper, a particular component of USLE (as well as MUSLE, RUSLE, and RUSLE2) is focused on the P-factor that represents the reduction in soil erosion that escapes from the study area (or off field) due to the effects of soil conservation measures such as terracing or proper ditch placement among other techniques such as tilling, contouring, and so forth. More specifically, the proper use of terraces (or elements that act similar to terraces such as ditches) results in sheet flow accumulating in terraces, and then the captured sediment-laden flow moving within the terrace confines at a significantly lower gradient, typically resulting in a flow velocity that promotes sediment deposition within the terrace. As a result of this deposition process, the eroded sediment transported by the sheet flow over the soil surface is captured by the terrace to a significant proportion of the total sediment load, with a corresponding reduction in lost sediment from the study area. That is, sediment that stays on the study site is sediment that is not lost from the site to flow downstream.

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The USLE and MUSLE formulations include tables of P-factors that describe the general efficiency of terraces and related elements in capturing sediment as described above (Foster and Highfill 1983; Wischmeier and Smith 1962, 1978; Wischmeier 1972, 1976; Smith and Wischmeier 1957, 1962). An example of a flood control agency use of the standard tabulations of P-factor values at the local level is found in the County of San Diego's Hydrology Manual (County of San Diego 2003). These tables are typically only developed with respect to the hydraulic variable of terrace grade. Although considerably effective in general application, such tabulations can be vastly improved by including the hydraulic effects of the other hydraulic variables that describe the flow of sediment-laden water in drainage elements such as terraces and ditches. The hydraulic variables of terrace cross section geometry and friction properties, the flow hydrograph, the longitudinal slope, and a sediment transport formula are all well-known parameters that are commonly used in the analysis of sediment transport in drainage elements.

The RUSLE (Renard et al. 1997) and RUSLE2 methodologies take a significant step forward in better describing and estimating the depositional effects of terraces and ditches beyond the initial procedure embodied in the USLE. RUSLE2 (Foster et al. 2003) takes the step of developing a computer program that builds the relevant computations, including depositional effects of terraces and ditches. However, these computer modeling methods do not fully describe the sediment transport relationship that occurs in terraces and ditches. The importance of properly modeling such depositional effects is apparent in the increased computational effort made in RUSLE2 to estimate the additional depositional effects afforded by terraces and ditches beyond those effects estimated by USLE alone.

In the current paper, a complete sediment transport modeling approach is developed for use in analyzing the sediment transport effects in terraces and ditches in order to augment the estimation procedures contained in the above-mentioned equations and procedures (i.e., USLE, MUSLE, RUSLE and RUSLE2, hereafter collectively called "USLE-based models"). The literature describes use of other modeling approaches for the assessment of the USLE factors, including the P-factor, such as the program Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2010). In the current paper, the well-known sediment transport model FLUVIAL-12 is the basis for modeling the complete sediment transport regime in order to better predict an appropriate P-factor value to be used for actual field conditions. The procedure presented is an extension of FLUVIAL-12 (Chang 1988) to accommodate small-scale watercourses such as terraces and similarly sized ditches. FLUVIAL-12 is a broad-ranged capability model of sediment transport and is accepted by numerous governmental agencies, including the US Army Corps of Engineers, the US Fish and Wildlife Service, California Department of Fish and Game, California State Water Resources Control Board, and several other state and local agencies. Details of the FLUVIAL-12 application are provided in the section below. By using FLUVIAL-12, detailed sediment transport analysis of terraces and ditches can be achieved and a corresponding P-factor can be developed for actual field conditions, where the developed P-factor includes all of the relevant hydraulic influences involved in sediment transport rather than only considering just a subset of the total parameter set as accomplished in the USLE-based models. The use of computer models to better estimate P-factors, such as the computer program SWAT, has been reported in the literature (Neitsch et al. 2010). However in the current paper, computer program FLUVIAL-12 is used, which is a computer program that models the entire sediment transport regime in a movable bed that includes the effects of erosion and deposition (Chang 2006).

FLUVIAL-12 APPLICATION FOR CALIBRATION OF P-FACTOR

The FLUVIAL-12 model simulates the hydraulics of open channel flow, sediment transport, and changes in channel geometry during a flow period using small time steps. The model uses cross sections similar to the US Army Corps of Engineers' Hydrologic Engineering Center River Analysis System (HEC-RAS) and HEC-2 models. Computations of water surface elevation and bed changes are carried to the precision of less than 0.01 foot at a time step. This high precision is essential because thousands of time steps are usually used for an analysis. High precision is applied to avoid accumulated computational error.

The FLUVIAL-12 model determines the interrelated changes in channel profile and channel width at each cross section based upon a stream's tendency to seek uniformities in sediment discharge and power expenditure. At each time step, scour and fill of the bed are computed based on the spatial variation in sediment discharge along the channel. Channel-bed corrections for scour and fill will reduce the nonuniformity in sediment discharge. Width changes are also made at each time step, resulting in a movement toward uniformity in power expenditure along the channel. Because the energy gradient is a measure of the power expenditure, uniformity in power expenditure also means a uniform energy gradient or linear water surface profile. A river, creek, or other channel may not have a uniform power expenditure or linear water surface profile, but it is constantly adjusting itself toward that direction. The model was calibrated using twelve sets of field data. Such calibration studies are listed in the FLUVIAL-12 User's Manual (Chang 2006).

An executable version of FLUVIAL-12 with the ability to model up to ten cross sections is available with sample input files and the relevant program documentation at the Web site, http://chang.sdsu.edu/fluvial.html. This downloadable program will allow the interested user to estimate P-factor values for their own projects.

EXAMPLE: CALIBRATION OF TERRACE P-FACTOR IN TERRACE

The high precision variation of the FLUVIAL-12 application discussed above is a general purpose computer model that can be applied to a wide range of situations that occur in the field regarding use of terraces and ditches. Such erosion control elements are found in a wide variety of geometries and grades. The FLUVIAL-12 is applied to the entire reach of terrace, even though terrace geometry and grade and friction properties may change along the terrace itself. Use of the computer program requires geometric description of the terrace by cross-sectional information, including soil properties and friction properties. Using the USLE-based model estimate of flow rate and sediment loss that enters the study terrace or ditch, the FLUVIAL-12 model is run and resulting sediment deposition or erosion estimated at each cross section.

To demonstrate the use of this program, a 122 m (400 ft) long terrace with cross section geometry shown in figure 1 was analyzed. The Engelund and Hansen (1967) sediment transport formula was selected based on the evaluation of sediment formulas by Brownlie (1981). Three different flow conditions were analyzed for study purposes: the 2-, 10-, and 100-year flood events. Other flow conditions were easily considered by simply rerunning the program with the desired flow conditions.

Typical FLUVIAL-12 summary output is included in table 1 (for the 2-year flood event near the end of the flow hydrograph). The summary output lists for each cross section (SECTION) the water surface elevation (W.S.ELEV.), flow width at the surface (WIDTH), flow depth (DEPTH), flow discharge (Q), mean flow velocity (V), energy gradient (SLOPE), median sediment load size (D50), ratio of bed material discharge to flow discharge (QS/Q), Froude number (FR), and sediment weight passing a cross section since the beginning of the simulation (SED. YIELD). Cross section 1 is at the downstream end of the 122 m (400 ft) long terrace and cross section 400 is at the upstream end. The cross sections are num-

Figure 1

Cross section of terrace modeled in FLUVIAL-12.

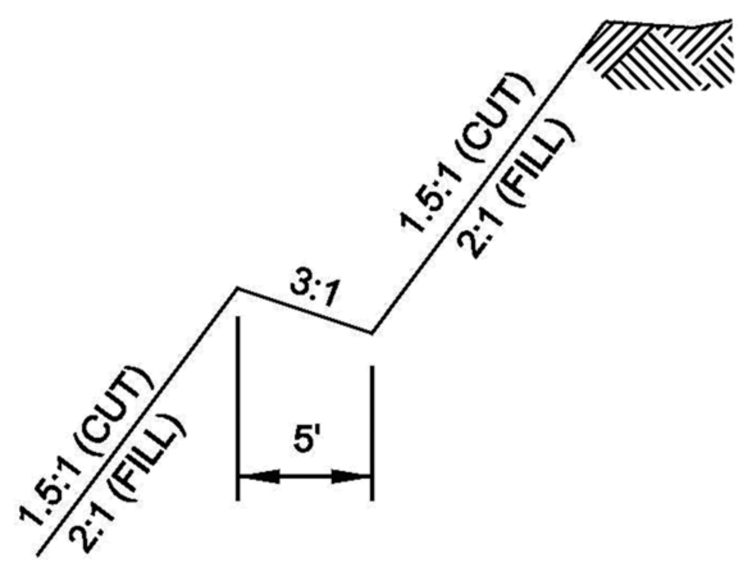


Table 1

Typical FLUVIAL-12 output.

SECTION	W.S.ELEV. FT	WIDTH FT	DEPTH FT	Q CFS	V FPS	SLOPE	D50 MM	QS/Q 1000 PPM	FR	SED. YIELD TONS
1.000	100.25	1.2	0.24	0.18	1.18	0.018548	0.93	1.895	0.60	0.342E+00
10.000	100.43	1.1	0.28	0.18	1.17	0.016138	0.76	1.475	0.55	0.423E+00
20.000	100.61	1.1	0.26	0.18	1.26	0.020022	0.75	2.853	0.61	0.505E+00
30.000	100.81	1.1	0.26	0.18	1.25	0.019855	0.66	3.140	0.61	0.531E+00
40.000	101.01	1.1	0.26	0.18	1.24	0.019501	0.64	3.212	0.61	0.554E+00
60.000	101.41	1.1	0.26	0.18	1.22	0.018400	0.60	3.098	0.59	0.578E+00
80.000	101.81	1.1	0.27	0.18	1.21	0.018212	0.63	2.915	0.59	0.636E+00
100.000	102.21	1.1	0.27	0.18	1.21	0.017803	0.65	2.656	0.58	0.696E+00
120.000	102.61	1.1	0.27	0.18	1.19	0.017012	0.63	2.531	0.57	0.768E+00
140.000	103.01	1.1	0.28	0.18	1.18	0.016637	0.58	2.764	0.56	0.875E+00
160.000	103.41	1.1	0.28	0.18	1.16	0.015485	0.61	2.498	0.54	0.987E+00
180.000	103.81	1.1	0.29	0.18	1.10	0.013387	0.62	1.894	0.51	0.110E+01
200.000	104.21	1.1	0.30	0.18	1.09	0.013075	0.69	1.511	0.50	0.119E+01
220.000	104.61	1.1	0.28	0.18	1.14	0.014890	0.64	2.037	0.53	0.127E+01
240.000	105.01	1.1	0.28	0.18	1.13	0.014561	0.74	1.972	0.53	0.135E+01
260.000	105.41	1.1	0.29	0.18	1.07	0.012741	0.78	1.499	0.49	0.139E+01
280.000	105.81	1.1	0.30	0.18	1.07	0.012453	0.75	1.172	0.49	0.142E+01
300.000	106.21	1.1	0.29	0.18	1.10	0.013710	0.57	2.060	0.51	0.145E+01
320.000	106.61	1.1	0.30	0.18	1.04	0.011681	0.62	1.639	0.47	0.150E+01
340.000	107.11	1.5	0.23	0.18	0.99	0.013359	0.65	0.944	0.51	0.152E+01
360.000	107.36	1.0	0.29	0.18	1.19	0.016086	0.73	2.262	0.55	0.163E+01
380.000	107.86	1.2	0.25	0.18	1.11	0.015463	0.54	2.346	0.55	0.164E+01
400.000	108.26	1.3	0.26	0.18	1.01	0.012336	1.09	2.304	0.49	0.170E+01

bered according to their distance along the 122 m (400 ft) long terrace. Figure 2 illustrates the 2-, 10-, and 100-year sediment yield along the channel reach starting from the downstream end. The numeric and graphic results indicate that under all flow events the yield decreases in the downstream direction along the terrace, which reflects deposition on the terrace. The ratio of sediment yield at a cross section to the initial sediment yield at the upstream cross section is used to obtain the P-factor. Figure 3 presents the P-factor along the terrace and shows that the P-factor at the lower end of the channel reach varies from 0.18 to 0.34.

For comparison purposes, the same sediment transport and channel geometry properties assigned to Example 1 are used for another example scenario where the channel length is 244 m (800 ft) instead of the prior 122 m (400 ft). The sediment yield and P-factor results are shown in figures 4 and 5, respectively. The resulting P-factor values, ranging from 0.22 to 0.27, again are similar to the usual tabulated values found

Figure 2

FLUVIAL-12 sediment yield along 400-foot terrace.

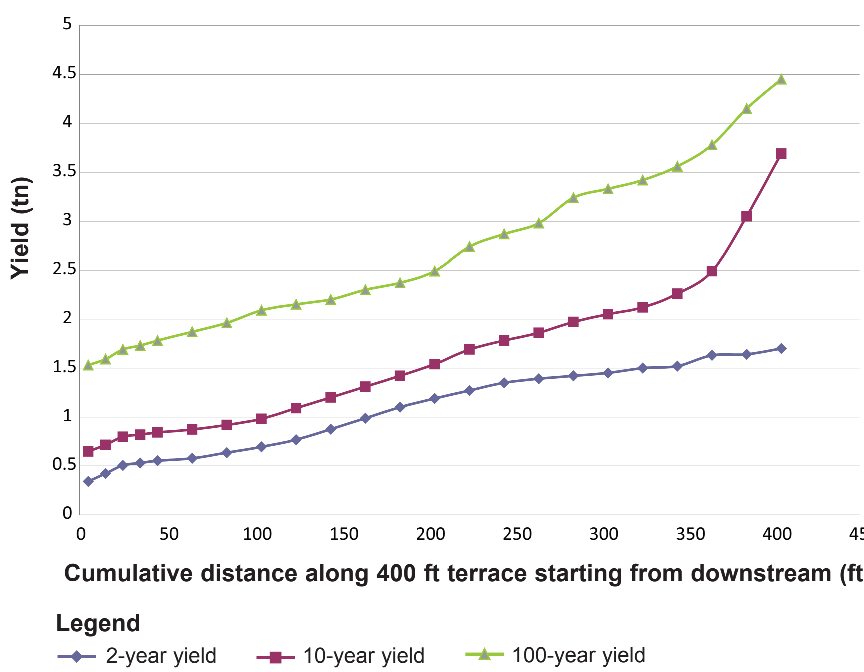


Figure 3

P-factor along 400-foot terrace.

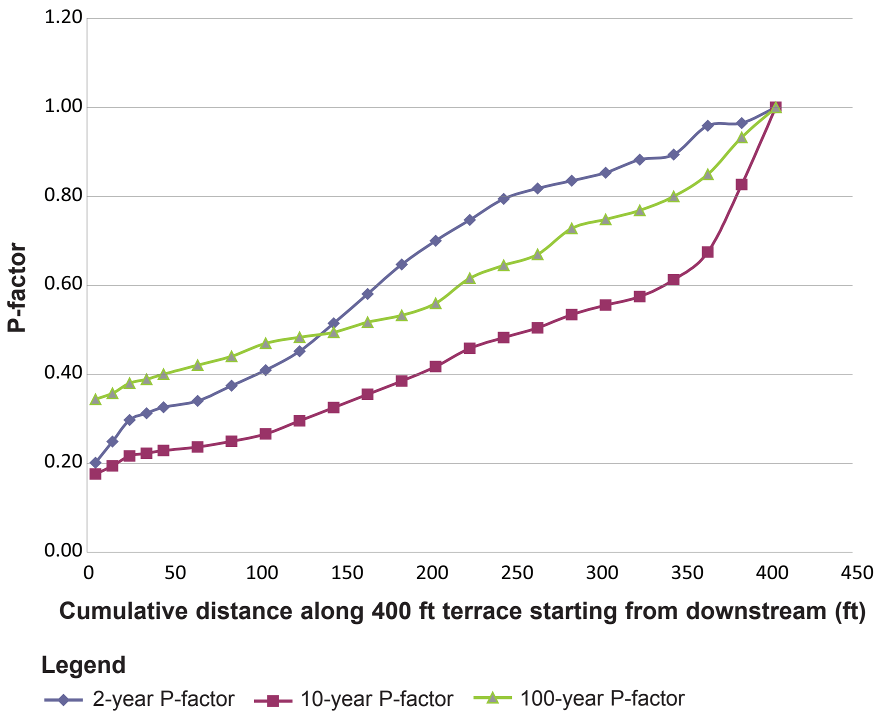
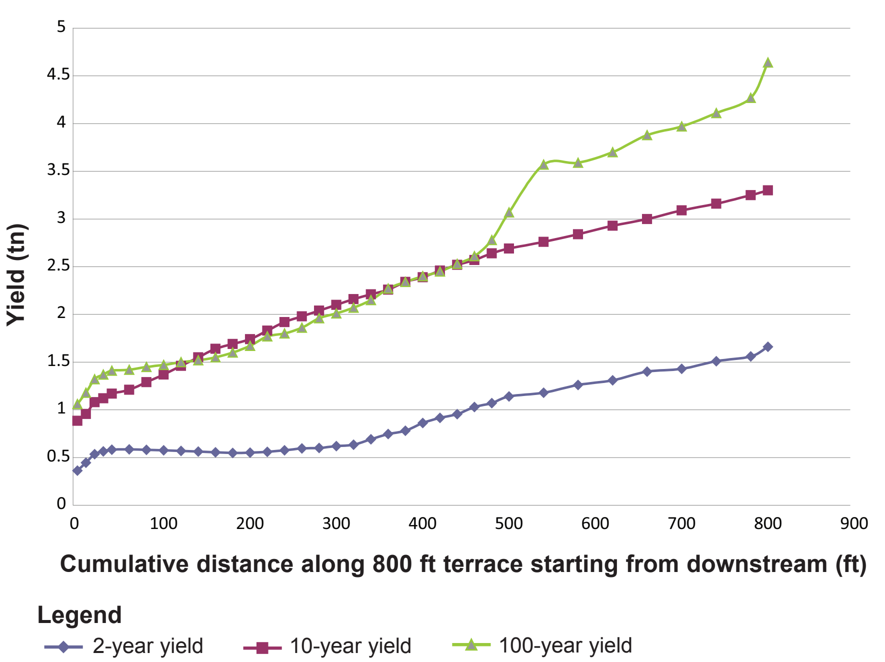


Figure 4

FLUVIAL-12 sediment yield along 800-foot terrace.



in the literature, but variations are seen with respect to storm return frequency, as observed with the prior example problem. A comparison of figures 2 and 3 with 4 and 5 demonstrates that the total channel impact upon sediment deposition on soil loss varies not only with storm magnitude (e.g., return frequency), but also for channelization effects such as channel length, which is the only variable that was changed from the 122 m (400 ft) to 244 m (800 ft) analyses. Consequently, using a computer model such as FLUVIAL-12 to model the entire sediment transport process provides a significant improvement in estimating the associated P-factor values for actual channel and flow conditions. The model allows the user to adjust several parameters and arrive at the appropriate P-factor for the selected parameters.

In many studies, there is a need for the estimation of annual sediment delivery (or annual soil loss) using return frequency analyses. The product of the net bed material yield with the corresponding flood event probability represents the stream's mean annual bed material yield from the given flood. The net bed material yield can also be plotted for various flood probabilities. The area under the curve provides an estimate of the mean annual sediment delivery (MacArthur et al. 1990).

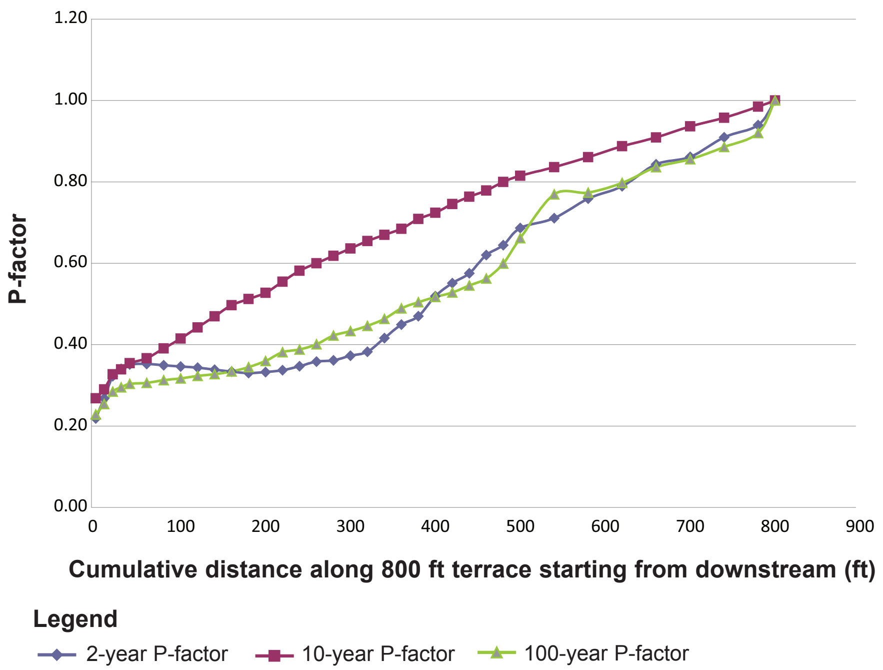
From the example problem computational results, depending on the return frequency of the design storm runoff, the proportion of the soil captured within the modeled terrace varies, as shown in the figures. The modeling results estimate values of sediment deposition that are equivalent to use of an USLE P-factor from about 0.20 to just over 0.30, which compares well with the traditional P-factor values published in the cited references. Analysis of other terrace or ditch geometries, slopes, friction factors, and other parameters and transport relationships, can be readily accomplished using the FLUVIAL-12 application. Of course, under different conditions and terrace situations, different sediment depositional rates will occur, which would be modeled in detail by the FLUVIAL-12 program.

SUMMARY AND CONCLUSIONS

A common problem facing soil conservation efforts is the estimation of soil loss from a study site and also estimation of the effects of sediment deposition that occurs in typical soil conservation elements such as terraces and ditches. The widely used Universal Soil Loss Equation and subsequent extensions form the underpinnings of numerous procedures used for estimating soil loss and off-field sediment delivery. In this paper, the computer pro-

Figure 5

P-factor along 800-foot terrace.



gram FLUVIAL-12 is presented as another technique for estimating the effects of sediment deposition in conservation elements such as terraces and ditches. The computer program can be applied to a wide variety of situations and can properly model the total sediment transport process in such conservation elements. Consequently, use of FLUVIAL-12 provides a more complete analysis of the sediment depositional process, enabling a more accurate calibration of the USLE (and subsequent extension methodologies) P-factor that is used in these soil-loss equations. The provided example problem analyses show that the FLUVIAL-12 analysis results in a calibration of the P-factor with a resulting value that closely matches the standard values found in the literature for general purpose conditions. Under different conditions, however, different P-factor values result.

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