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Successful application of the Taguchi method to simulated soil erosion experiments at the slope scale under various conditions

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ABSTRACT

The benefits of the Taguchi method have been demonstrated in diverse fields. However, its applicability to soil erosion experiments at the slope scale under various conditions remains unclear. Using 6 published datasets that included the dependent variables of erosion rate (D), runoff rate (R), sediment concentration (C), flow velocity (V) and transport capacity (Tc), we compared the results from the full-factorial design method with those from the Taguchi and orthogonal design methods to validate the applicability of the Taguchi method to simulated soil erosion experiments at the slope scale under different conditions. The statistical parameters of the dependent variables from the orthogonal design and Taguchi method were very close to those from the full-factorial design for all dependent variables. The trends of the main effects based on different factor levels were consistent for 35 out of 45 sets from the full-factorial design and Taguchi method and for 27 sets from the orthogonal design. The optimum conditions for 10 and 7 dependent variables (out of 14) for the Taguchi and orthogonal design methods were the same as those for the full-factorial design, respectively. In addition, 13 and 8 dependent variables (out of 14) for the Taguchi and orthogonal design methods had the same factor rank order of percentage contributions as the full-factorial design method, respectively. Based on a univariate analysis of variance, the evaluating indicators for predictive power, including the determination coefficient, Nash-Sutcliffe efficiency, relative root mean squared error, mean absolute percentage error and Thiel inequality coefficient, indicated that the Taguchi method predictions were better than the orthogonal design predictions. Overall, the Taguchi method could obtain more reliable conclusions for soil erosion than the orthogonal design method at the slope scale. These findings suggest that the Taguchi method could be successfully applied to soil erosion experiments and could better replace the full-factorial design method at the slope scale compared with the orthogonal design method.

1. Introduction

Soil erosion is one of the most serious agro-environmental threats and consists of complex dynamic processes that depend on many influencing factors such as soil type, slope gradient, slope length, rainfall characteristics, hydraulic factors, ground cover, land use, human activities and their interactions (Meyer, 1981; Meyer and Harmon, 1989; Kinnell, 2005; Shi et al., 2012, 2019; Zhuang et al., 2015; Teixeira Guerra et al., 2017; Li et al., 2019a). To identify the effects of influencing factors and their interactions on soil erosion, understand soil erosion processes, improve soil prediction and develop proper conservation plans for erosion control, many experiments in the laboratory and field have been performed under various conditions (Zhuang et al., 2015). However, soil erosion experiments are time-consuming, costly and labor-intensive. Therefore, the number of experimental combinations must be reduced by developing a time-, cost- and labor-effective experimental design for factorial experiments on soil erosion under various conditions.

Full-factorial design has been generally applied to soil erosion studies when considering two or more factors (Meyer, 1981; Meyer and Harmon, 1989; Zhang et al., 1998, 2011, 2014; Li et al., 2019b). Theoretically, the full-factorial design is a classical and the most conservative experimental design (Box et al., 2005; Smucker et al., 2018), and it can provide the most sufficient information by investigating all possible combinations of the experimental factors at their respective application levels. Nevertheless, the number of experimental

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Table 1
Overview of the datasets used in this study.

Dataset No.	Experiment type	Factors	Number of levels	Range of level	Variables	Reference
Dataset 1	Simulated rainfall	ST	1		R, D, C and V	Deng (2014)
		‘S	1	47%		
		L	4	3–12 m		
		I	4	60–150 mm h^{-1}		
		SC	4	0–30%		
Dataset 2	Simulated rainfall	ST	1		R, D, C and V	Zhang et al. (2015)
		S	5	18–58%		
		L	5	0.4–2 m		
		I	5	48–170 mm h^{-1}		
Dataset 3	Simulated rainfall	ST	4		R, D and C	Meyer and Harmon (1989)
		S	4	5–30%		
		L	4	0.15–0.6 m		
		I	4	26.4–115 mm h^{-1}		
Dataset 4	Simulated rainfall	L	1	0.75 m	D	Watson and Laflen (1986)
		ST	3			
		S	3	10–50%		
		I	4	48–150 mm h^{-1}		
Dataset 5	Simulated flow	S	5	8.7–46.6%	V	Cao et al. (2011)
		CD	6	0–25%		
		FR	5	0.25–2 L s^{-1}		
Dataset 6	Simulated flow	S	5	8.7–42.3%	Tc	Zhang et al. (2011)
		D_{50}	5	0.10–1.16 mm		
		UFD	5	0.66–5.26 × 10^{-3} m^2 s^{-1}		

ST, soil type; ‘S, slope gradient (%); L, slope length (m); I, rainfall intensity (mm h^{-1}); SC, percentage of gravel in soil (%); CD, cover degree (%); FR, flow discharge (L s^{-1}); D_{50}, median diameter (mm); UFD, unit flow discharge (m^2 s^{-1}); R, runoff rate (mm h^{-1}); D, erosion rate (kg m^{-2} h^{-1}); C, sediment concentration (kg m^{-3}); V, flow velocity (m s^{-1}); Tc, transport capacity of overland flow (kg m^{-1} s^{-1}).

combinations exponentially grows with an increase in the number of factors and their levels so that full-factorial design is too time-consuming, costly and labor-intensive to run for most practical purposes (Box et al., 2005). To minimize the number of tests required and maximize the effectiveness, some efficient designs, i.e., fractional factorial designs, which are experimental designs consisting of a carefully chosen subset (fraction) of experimental runs from a full-factorial design, have been developed independently to estimate several main effects (Mee, 2009). Fractional factorial designs are useful for identifying important factors and producing useful initial experiments (Mee, 2009; Smucker et al., 2018). The orthogonal design and Taguchi method, which substantially reduce the number of experimental combinations, are two typical types of fractional factorial design matrices.

Rao (1947) first introduced the experimental design concept of orthogonal arrays, which are usually straightforward because each main effect and interaction can be estimated independently. The orthogonal experimental design is a highly efficient method that is capable of addressing multifactor experiments and screening optimum levels by using an orthogonal design table (Hedayat et al., 1999; Deng, 2000). The concept of orthogonal arrays was perfectly introduced and played a central role in the development of Taguchi methods (Taguchi, 1959, 1960). Taguchi developed a system of tabulated designs (arrays) that allows for the maximum number of main effects to be estimated in an unbiased manner while using only a minimum number of experimental tests (Taguchi, 1990). Compared with the orthogonal design, the S/N (signal-to-noise) ratio was introduced into the Taguchi method to quantify the quality of the characteristics of the product in terms of the respective product’s response to noise factors and signal factors (Taguchi and Phadke, 1989; Taguchi, 1990). The main advantages of the Taguchi method and its defects have been summarized (Nair et al., 1992). The Taguchi method is economical and efficient because it requires a minimum number of experimental tests, and its conclusions are associated with statistical levels of confidence (Taguchi and Phadke, 1989; Taguchi, 1990; Nair et al., 1992; Hedayat et al., 1999; Deng, 2000); thus, it has been widely and successfully implemented in diverse fields as summarized in detail by Sadeghi et al. (2012).

In the field of soil erosion studies, Sadeghi et al. (2012) identified the effects of soil texture, slope, aspect and vegetation cover on soil loss and estimated the partial contribution of each of the factors to soil loss by using the Taguchi method. Sun et al. (2018) elucidated the effects of slope, flow discharge and freeze-thaw factors on soil detachment capacity by using the Taguchi method. Nevertheless, soil erosion is affected by complex dynamic processes. Many factors can affect soil erosion, and the effects of these factors might vary under different spatial scales and conditions. The different types of soil erosion, including splash, interrill, rill, ephemeral gully and gully, might occur with an increase in rainfall intensity, slope size and slope degree on a sloped surface. Different parameters, such as erosion rate, runoff rate, flow velocity and sediment concentration, have been measured and calculated during experiments. In addition, many different types of soil erosion experiments have been performed according to specific objectives, such as experiments on the transport capacity, interrill erosion, rill erosion and detachment of soil. Although Zhang et al. (2015) indicated that the Taguchi method could mainly replace full-factorial design in interrill erosion studies, widely applying the Taguchi method to soil erosion studies under various conditions may be inappropriate as a replacement for the full-factorial design method. Additionally, for soil erosion studies, the results from the Taguchi method and orthogonal design that are closest to the results from the full-factorial design method must be identified. The reliability of the results from the Taguchi method as well as the differences between the results from a full-factorial design and that of the orthogonal design and Taguchi methods remain unclear in the field of soil erosion studies under various conditions.

Therefore, in the present study, published data were used to assess the applicability of the Taguchi method for simulated soil erosion experiments at the slope scale under various conditions by comparing the differences in the results among the full-factorial design, orthogonal design and Taguchi methods. The results from this study will provide basic support for using the Taguchi method in soil erosion studies at the slope scale under various conditions, accelerate the accumulation of soil erosion knowledge and promote the development of soil erosion theory.

2. Materials and methods

2.1. Dataset collection

Five available peer-reviewed publications and one master's thesis on soil erosion that included no less than three factors and three levels of each factor were collected from the Web of Science and China National Knowledge Infrastructure in this study (Table 1). The raw data were either obtained from tables or extracted by digitizing graphs using the GetData Graph Digitizer (version 2.24, Russian Federation). The detailed descriptions of the collected datasets are as follows:

Dataset 1: This dataset was from Deng's master's thesis in Chinese with an English abstract (Deng, 2014), and it aimed to study the effect of building projects on soil erosion by stimulated rainfall experiments. The study considered one soil type (Lou soil), one slope gradient (47%), four percentages of gravel (diameter: 1–2 cm) in soil (0%, 10%, 20% and 30%), four slope lengths (3, 5, 6.5 and 12 m with a width of 1.5 m) and four rainfall intensities (60, 90, 120 and 150 mm h^{-1}). A full-factorial design was used, and 64 tests were conducted. The observation variables considered in this dataset were erosion rate (D), runoff rate (R), sediment concentration (C) and flow velocity (V).

Dataset 2: This dataset has been used to assess the applicability of the Taguchi design method to an interrill erosion study (Zhang et al., 2015). The study simulated rainfall experiments and considered one soil type (loessial soil), five slope lengths (0.4, 0.8, 1.2, 1.6, and 2 m), five slope gradients (18%, 27%, 36%, 47%, and 58%), and five rainfall intensities (48, 62.4, 102, 149, and 170 mm h^{-1}). A full-factorial design was used, and 125 tests were conducted. The observation variables considered in this dataset were erosion rate (D), runoff rate (R), sediment concentration (C) and flow velocity (V).

Dataset 3: This dataset was published by Meyer and Harmon (1989), who evaluated the effect of row-side slope length and steepness on side slope erosion for different soils and a range of runoff-producing rain intensities by simulated rainfall. This study included four soil types (Brooksville, Atwood, Dubbs, Loring), four slope lengths (0.15, 0.3, 0.45 and 0.6 m with a width of 0.3 m), four slope gradients (5%, 10%, 20% and 30%) and four rainfall intensities (very low: 13.6–14, low: 26.4–27, medium: 74.3–76.3 and high: 112–115 mm h^{-1}). A full-factorial design was used, and 256 combinations were conducted. Two of the combinations were unavailable. The observation variables considered in this dataset were erosion rate (D), runoff rate (R) and sediment concentration (C).

Dataset 4: This dataset was collected from the study published by Watson and Laflen (1986) who investigated the effects of soil strength, slope and rainfall intensity on interrill erosion under simulated rainfall. This study included one slope length (0.75 m with a width of 0.75 m), three soil types (Clarion, Monona, Readlyn), three slope gradients (10%, 20% and 50%) and four rainfall intensities (48, 66, 106, and 150 mm h^{-1}). A full-factorial design was used, and 36 tests were conducted. To facilitate the design of an appropriate orthogonal table, 27 tests out of 36 were used, and the rainfall intensity levels were 66, 106, and 150 mm h^{-1}. The observation variable considered in this dataset was erosion rate (D).

Dataset 5: This dataset was published by Cao et al. (2011) in Chinese with an English abstract, and their objective was to exploit the relationships between the average overland flow velocity and coverage rate, slope degree and discharge in an experimental flume (5 m long, 0.4 m wide and 0.27 m depth) under simulated flow. This study considered six simulated cover degrees (0%, 5%, 10%, 15%, 20% and 25%), five flow rates (0.25, 0.5, 1.0, 1.5 and 2 L s^{-1}) and five slope gradients (8.7, 17.6, 26.8, 36.4 and 46.6%). A full-factorial design was used, and 150 tests were conducted. To facilitate the design of an appropriate orthogonal table, 125 out of 150 tests were used, and the levels of simulated cover degree were determined as 5%, 10%, 15%, 20% and 25%. The observation variable considered in this dataset was flow velocity (V). The raw data were extracted by digitizing graphs using the GetData Graph Digitizer (version 2.24, Russian Federation).

Dataset 6: This dataset was published by Zhang et al. (2011), who investigated the effects of sediment size on the transport capacity of overland flow in a hydraulic flume over a wide range of flow discharge and slope gradient values under simulated flow. This study considered five classes of sediment size (0.02–0.15, 0.15–0.25, 0.25–0.59, 0.59–0.85 and 0.85–2.00 mm with median diameter (D_{50}) values of 0.10, 0.22, 0.41, 0.69 and 1.16 mm, respectively), five unit flow discharges (0.66, 1.32, 2.63, 3.95 and 5.26 $\times 10^{-3}$ m^2 s^{-1}) and five slope gradients (8.7, 17.4, 25.9, 34.2 and 42.3%). A full-factorial design was used, and 125 tests were conducted. The variable considered in this dataset was transport capacity (T_c).

2.2. Analytical method

2.2.1. Selection of an orthogonal table

A full-factorial design was used in all datasets described above. As alternative approaches, the orthogonal design and Taguchi method were applied to these datasets. According to the rules of orthogonal design and Taguchi method, the orthogonal table for dataset 1 was an $L_{16}(4^3)$ orthogonal array, those for datasets 2, 5 and 6 were $L_{25}(5^3)$ orthogonal arrays, that for dataset 3 was an $L_{16}(4^4)$ orthogonal array and that for dataset 4 was an $L_9(3^3)$ orthogonal array. These orthogonal tables were generated in Minitab 17, and the data selected from each dataset were used.

2.2.2. Calculation of the S/N ratio

Except for converting the values of the dependent variable to the S/N ratio, the procedures for the Taguchi method were the same as those for the orthogonal design. The detailed procedures for using the Taguchi method are shown in the previous studies (Sadeghi et al., 2012; Zhang et al., 2015; Sun et al., 2018). For convenience, the details are also described here. An analysis of the signal-to-noise (S/N) ratio is needed to determine the deviation of the quality characteristics from the desired value and evaluate the experimental results obtained by the Taguchi method. The signals are indicators of the effect on average responses, and the noises are measures of the influence on the deviations from the sensitivity of the dependent variables to noise factors (Lakshminarayanan and Balasubramanian, 2008). Three types of S/N ratio analyses are generally applicable: the higher-the-better (HTB), nominal-the-better (NTB) and lower-the-better (LTB). In practical terms, the appropriate type of S/N ratio analysis is chosen according to previous knowledge, expertise, the literature and an understanding of the process. In the study of soil erosion, the most important targets are the amount of soil that was eroded under the given conditions and the optimum treatment conditions under which maximum soil erosion would occur (Sadeghi et al., 2012). In this situation, a higher soil erosion rate is desirable to show the seriousness of soil erosion, express the role of influencing factors and develop proper conservation plans for erosion control. In contrast, smaller values are undesirable. Obviously, the NTB analysis is not suitable for soil erosion studies. Therefore, the HTB analysis was used. The S/N ratio was calculated by the following equation (Taguchi, 1990):

$$\frac{S}{N} = -10\mathrm{Log}_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{1}$$

where n is the number of repetitions and y is an observed value for a dependent variable, such as the erosion rate, runoff rate, sediment concentration, flow velocity and flow transport capacity in this study.

2.2.3. Determining the combination of optimum conditions

The analysis of means statistical approach was used to determine the optimum conditions under which the maximum value of dependent variables occurred (Sadeghi et al., 2012). First, the mean of the S/N ratios for each factor at a certain level was calculated by the following

Table 2

Statistical parameters of the dependent variables for different designs.

Datasets	Variable	Method	N	Max.	Min.	Mean	SD	CV
Dataset 1	R	FFD	64	149.38	34.84	79.84	30.66	0.38
		OD/TD	16	129.91	34.84	76.86	30.37	0.40
	D	FFD	64	32.13	0.66	8.08	7.55	0.93
		OD/TD	16	32.13	0.75	8.38	9.35	1.12
	C	FFD	64	249.70	16.23	85.99	59.74	0.69
		OD/TD	16	249.70	19.29	89.57	75.38	0.84
	V	FFD	64	0.52	0.05	0.14	0.09	0.62
		OD/TD	16	0.52	0.05	0.15	0.12	0.82
Dataset 2	R	FFD	125	111.89	17.52	60.97	29.38	0.48
		OD/TD	25	111.89	18.33	60.96	30.56	0.50
	D	FFD	125	14.17	1.20	6.05	3.52	0.58
		OD/TD	25	13.79	1.20	6.29	3.86	0.61
	C	FFD	125	199.39	46.88	96.46	25.99	0.27
		OD/TD	25	199.39	54.98	99.71	32.59	0.33
	V	FFD	125	0.26	0.05	0.16	0.05	0.30
		OD/TD	25	0.25	0.05	0.16	0.05	0.30
Dataset 3	R	FFD	254	107.34	4.74	46.62	34.29	0.74
		OD/TD	16	99.66	6.36	46.64	36.33	0.78
	D	FFD	254	9.29	0.001	1.44	1.92	1.34
		OD/TD	16	5.16	0.001	1.26	1.58	1.26
	C	FFD	254	104.81	0.15	20.14	20.40	1.01
		OD/TD	16	51.79	0.15	18.26	16.00	0.88
Dataset 4	D	FFD	27	11.70	0.43	3.54	3.57	1.01
		OD/TD	9	10.91	0.65	3.61	3.69	1.02
Dataset 5	V	FFD	125	1.04	0.10	0.45	0.18	0.40
		OD/TD	25	1.04	0.17	0.45	0.20	0.45
Dataset 6	Tc	FFD	125	9.53	0.04	2.52	2.48	0.98
		OD/TD	25	9.53	0.07	2.53	2.68	1.06

R, runoff rate (mm h^{-1}); D, erosion rate (kg m^{-2} h^{-1}); C, sediment concentration (kg m^{-3}); V, flow velocity (m s^{-1}); Tc, transport capacity of overland flow (kg m^{-1} s^{-1}); FFD, full-factorial design; OD, orthogonal design; TD, Taguchi design; N, the number of tests; Max., the maximum value of one variable; Min., the minimum value of one variable; SD, standard deviation; CV, coefficient of variation.

formula:

$$(M)_{Factor=l}^{Level=i} = \frac{1}{n_{li}} \sum_{j=1}^{n_{li}} \left[\left(\frac{S}{N}\right)_{Factor=l}^{Level=i} \right]_j \tag{2}$$

where $(M)_{Factor=l}^{Level=i}$ is the mean of the S/N ratios for factor *l* at level *i*, and n_{li} is the number of occurrences of factor *l* at level *i*. The optimum conditions were then identified as those producing the highest mean value of the S/N ratios for each factor at a particular level. The full-factorial and orthogonal designs could also identify the optimum conditions by replacing the S/N ratio with the measured value of the dependent variable.

2.2.4. *Determination of the trend of the main effect of the factor*

A main effect is the effect of an independent variable on a dependent variable averaged across the levels of any other independent variable. According to Eq. (2), the averages of the dependent variable values (i.e., runoff rate, erosion rate, sediment concentration, flow velocity and transport capacity of overland flow in this study) and their S/N ratio for each factor at a particular level were calculated for the treatments from the full-factorial design, orthogonal design and Taguchi method. In this study, these averages were normalized using the zero-mean normalization method to benefit the comparison and plotting. A normalized value (M_i^*) is obtained from the following expression:

$$(M_i^*)_{factor=l}^{Level=i} = \frac{(M)_{factor=l}^{Level=i} - (M)_{factor=l}^{\bar{Level}=i}}{S_x} \tag{3}$$

where $(M)_{factor=l}^{\bar{Level}=i}$ is the average value of $(M)_{factor=l}^{Level=i}$ of factor *l* and S_x is the standard deviation of $(M)_{factor=l}^{Level=i}$ of factor *l*. In this study, the normalized values only indicate the change trends in the levels of the factors.

2.2.5. *Calculating the percentage contribution (PC) of each factor*

The influence of each factor on the dependent variables was statistically assessed by a univariate analysis of variance (ANOVA) (Chou et al., 2009; Sadeghi et al., 2012). The percentage contribution (PC) of each factor to the variation in the dependent variable was calculated by the following equation:

$$\text{PC} = \frac{SS_F - (DF * V_{Er})}{SS_T} \times 100 \tag{4}$$

where SS_T is the total sum of squares, SS_F is the factorial sum of squares, V_{Er} is the variance in the error, and *DF* is the degrees of freedom. The values of *DF*, SS_T, SS_F and V_{Er} were obtained from the ANOVA. The Minitab 17 software package, in which there are submenus for the Taguchi method and ANOVA, was used to apply the Taguchi, full-factorial and orthogonal design methods.

2.2.6. *Predictions and evaluating indicators*

Using the Minitab 17 software package, the values of the dependent variables and their S/N ratios under all possible combinations of the experimental factors at their respective application levels could be predicted by analyzing the experimental data from the orthogonal design and the corresponding S/N ratios from the Taguchi method. The values of the dependent variables as the predicted values from the Taguchi method were subsequently derived by Eq. (1) according to the predicted values of the S/N ratios.

Five evaluating indicators, namely, the coefficient of determination (R^2), Nash-Sutcliffe efficiency coefficient (NSE), relative root mean squared error (RRMSE), mean absolute percentage error (MAPE) and Thiel inequality coefficient (TIC), were used to evaluate the predictive power of both the orthogonal design and the Taguchi method by ANOVA. R^2, NSE, RRMSE, MAPE and TIC were calculated as follows:

$$R^2 = \frac{[(\sum_{i=1}^{n}(M_i - \bar{M})(P_i - \bar{P}))]^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2} \tag{5}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(M_i - P_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \tag{6}$$

$$\text{RRMSE} = 1 - \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - P_i)^2}}{\frac{1}{n}\sum_{i=1}^{n} M_i} \tag{7}$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{P_i - M_i}{M_i} \times 100\right| \tag{8}$$

$$TIC = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - M_i)^2} / \sqrt{\frac{1}{n}\sum_{i=1}^{n}P_i^2} + \sqrt{\frac{1}{n}\sum_{i=1}^{n}M_i^2} \tag{9}$$

where n is the number of observations, M_i is the measured value of the observation variable of the i-th combination, P_i is the predicted value of the observation variable of the i-th combination and $\bar{M}$, and $\bar{M}$ and $\bar{P}$ are the average values of the measured values and the predicted values, respectively, for all combinations. The values of R^2 and TIC are between 0 and 1.0. The value of NSE can range from $-\infty$ to 1.0. The value of RRMSE is less than or equal to 1.0. Values of MAPE is greater than 0%. The values of R^2, NSE and RRMSE closer to 1.0 indicate better predictions, whereas values of MAPE and TIC closer to 0 indicate better predictions.

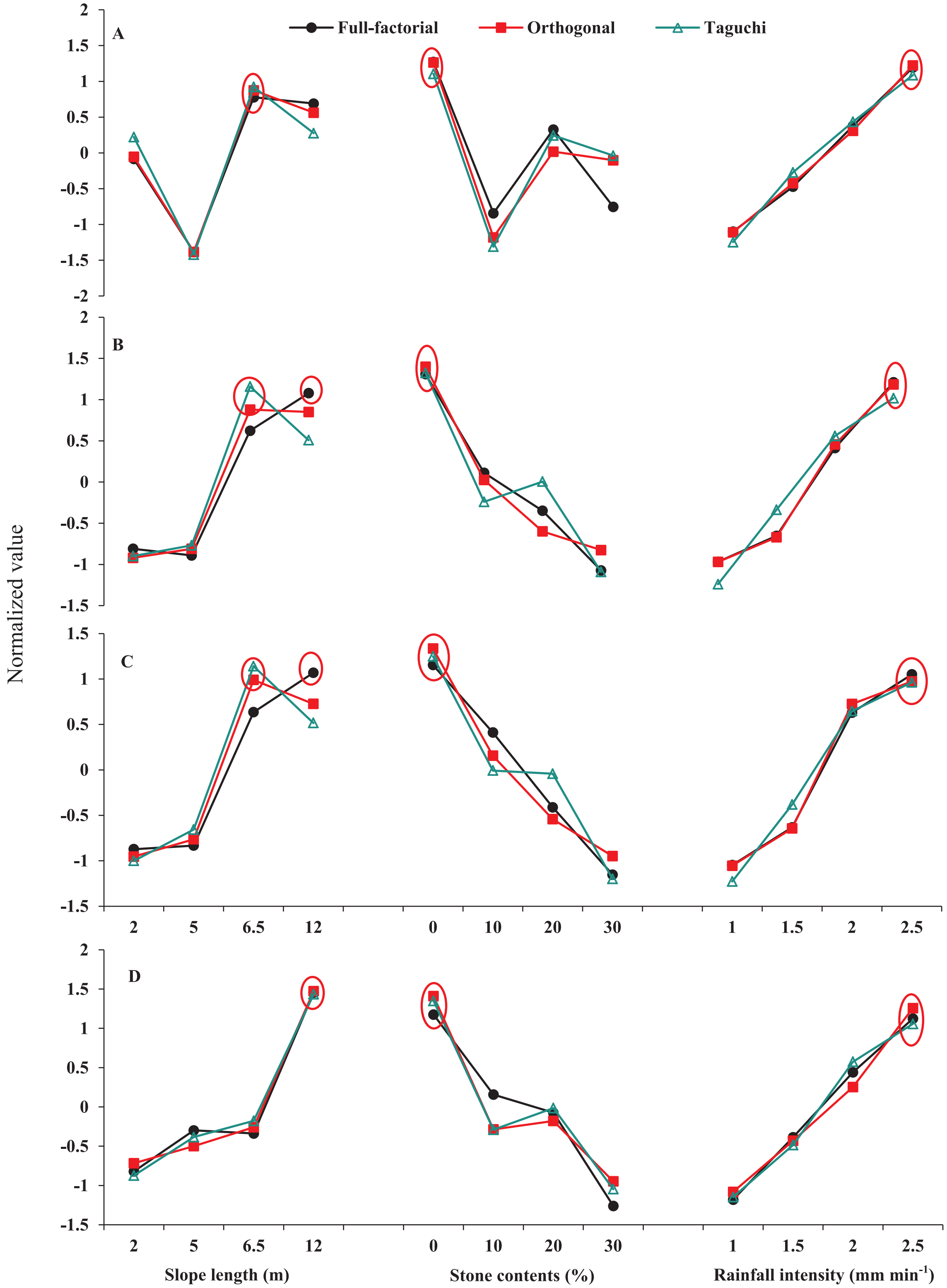

Fig. 1. Main effects of slope length, stone content and rainfall intensity for the dependent variables of runoff rate (A), erosion rate (B), sediment concentration (C) and flow velocity (D) in dataset 1 obtained from the full-factorial design, orthogonal design and Taguchi method.

3. Results

3.1. Statistical parameters

The same experimental combinations that were selected according to the orthogonal tables were applied to the Taguchi method and orthogonal design in this study. For all study datasets, the relevant statistical parameters for the dependent variables were calculated based on the data from the full-factorial design and orthogonal/Taguchi design methods (Table 2). In comparison to the full-factorial design, the number of tests was significantly reduced by 66.67 − 93.73% for the orthogonal/Taguchi design, and these reductions were enhanced with

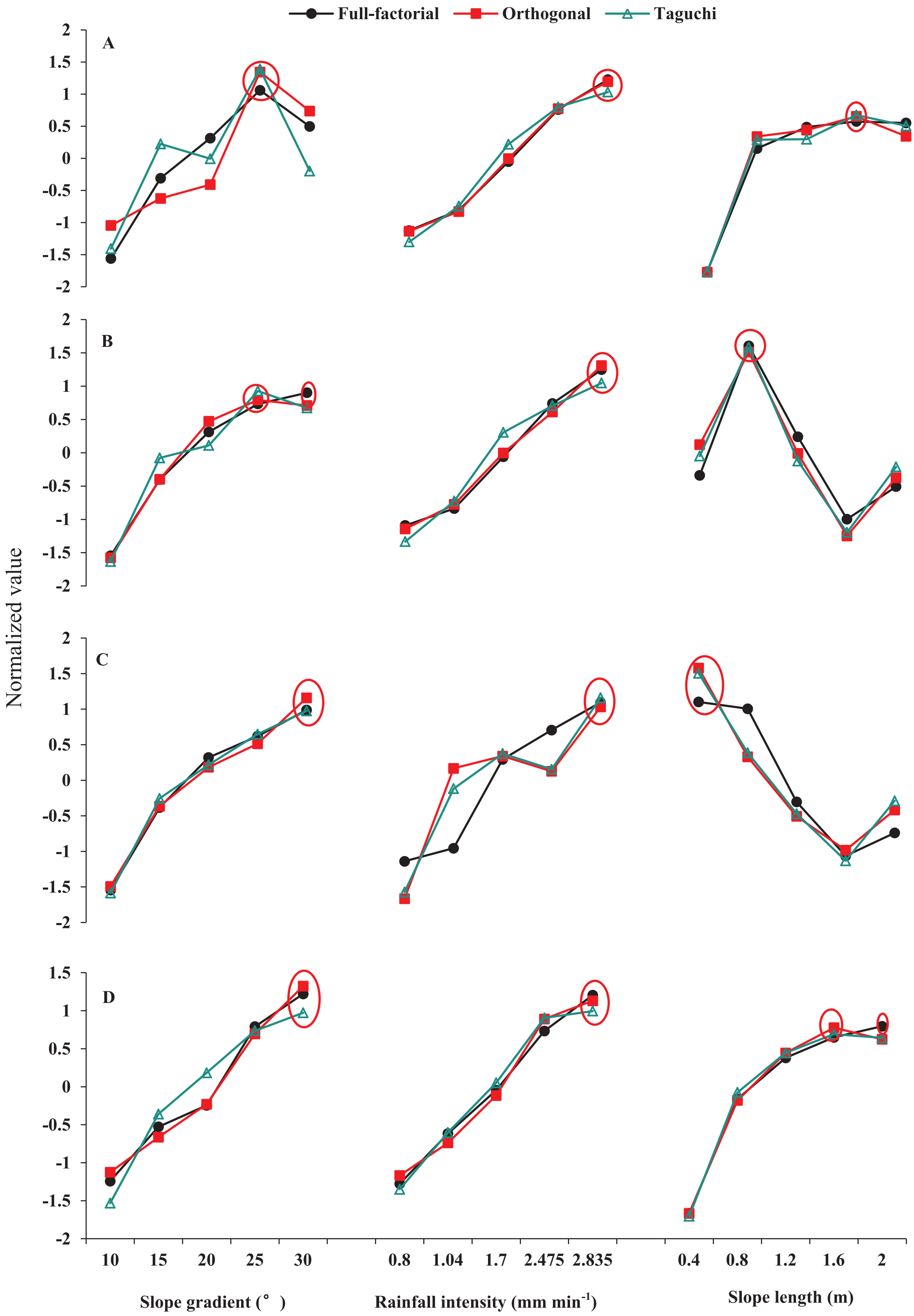

Fig. 2. Main effects of slope gradient, rainfall intensity and slope length for the dependent variables of runoff rate (A), erosion rate (B), sediment concentration (C) and flow velocity (D) in dataset 2 obtained from the full-factorial design, orthogonal design and Taguchi method.

increasing influencing factors and their levels. Fourteen dependent variables in six datasets were analyzed. The maximum values were the same between the full-factorial and the orthogonal/Taguchi design for 7 out of 14 dependent variables, and the minimum values were the same for 6 out of 14 dependent variables. There were only 2 dependent variables with different maximum and minimum values among these three designs. The differences in the maximum or minimum values between the full-factorial design and the orthogonal/Taguchi design

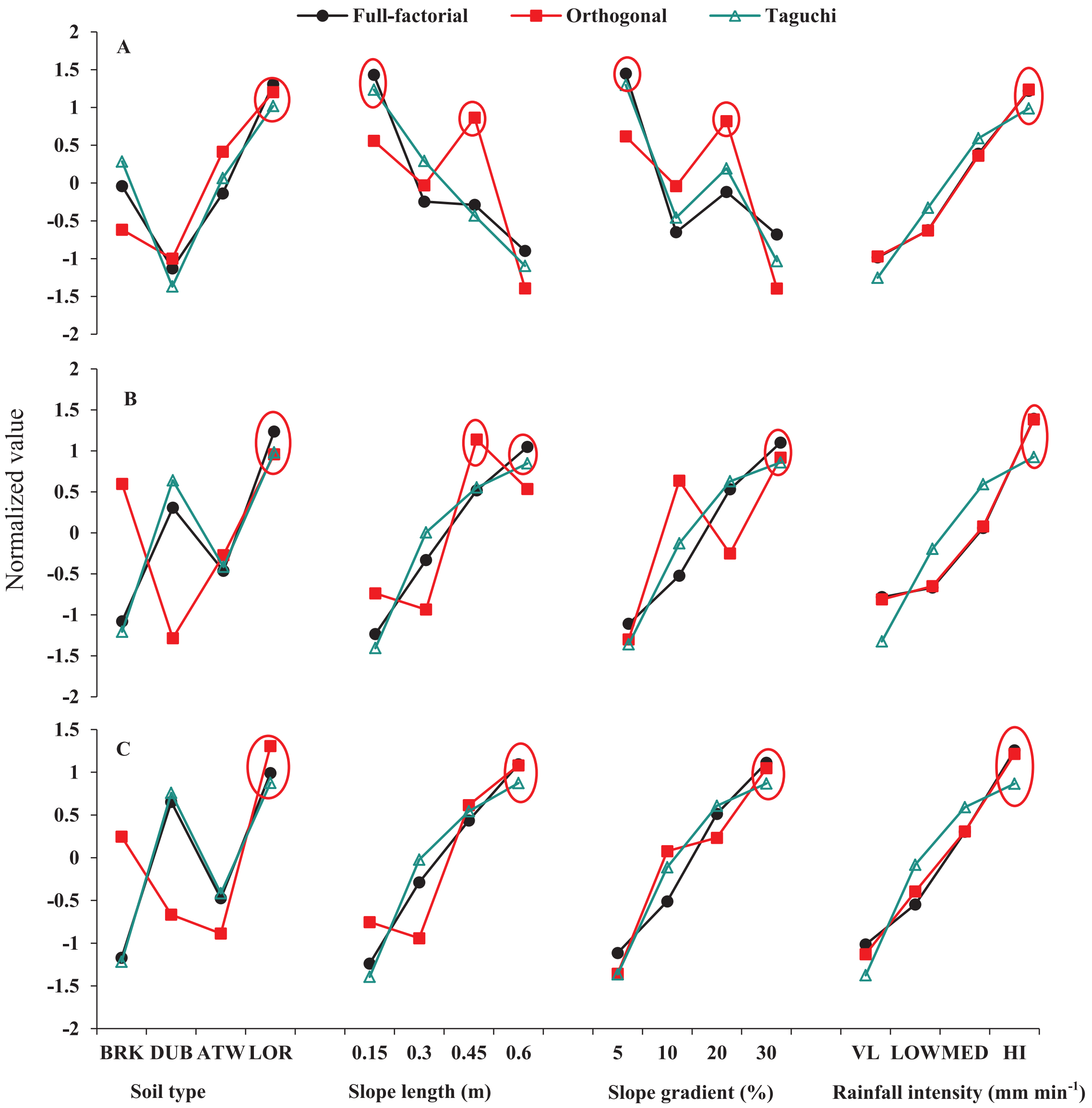

Fig. 3. Main effects of soil type, slope length, slope gradient and rainfall intensity for the dependent variables of runoff rate (A), erosion rate (B) and sediment concentration (C) in dataset 3 obtained from the full-factorial design, orthogonal design and Taguchi method.

were small for most of the dependent variables. The average from the full-factorial design was very close to that from the orthogonal/Taguchi design for all dependent variables, and the relative differences ranged from 0.03% to 12.45%. The coefficient of variation from the orthogonal/Taguchi design was greater than that from the full-factorial design, but the differences were small. Generally, the values of the common statistical parameters from the orthogonal/Taguchi design were almost consistent with those from the full-factorial design for most dependent variables in the datasets of this study.

3.2. Trends of the main effects with factor levels

Figs. 1–4 present the trends of the changes in the main effects with the factor levels for all dependent variables from the full-factorial design, orthogonal design and Taguchi method. A total of 45 sets of change trends were identified for the main effects with different factor levels in this study. The trends obtained separately from these three methods were consistent for 25 out of 45 sets. The trends obtained from full-factorial and orthogonal designs were consistent for 27 out of 45 sets, those from the full-factorial design and Taguchi method were consistent for 35 out of 45 sets, and those from the orthogonal design and Taguchi method were consistent for 32 out of 45 sets. For all datasets, the inconsistent sets most commonly occurred in the dataset published by Meyer and Harmon (1989) (Fig. 3). In general, compared with the orthogonal design results, the results of the trends of the main effects with various factor levels from the Taguchi method were closer to those from the full-factorial design.

3.3. Optimum conditions

According to the main effect analysis for each factor, the optimum conditions were identified as those producing the highest average measured values for the dependent variables and the S/N ratios for each factor at a particular level. The optimum conditions are also displayed as small red circles in Figs. 1–4. For the 14 dependent variables, the same optimum conditions were obtained between these three methods for 7 dependent variables, between the full-factorial and orthogonal design methods for 7 dependent variables, between the full-factorial design and Taguchi methods for 10 dependent variables and between the orthogonal design and Taguchi method for 11 dependent variables. Compared with the conditions of the measured maximum value (Table 3), the optimum conditions of 7 dependent variables from the

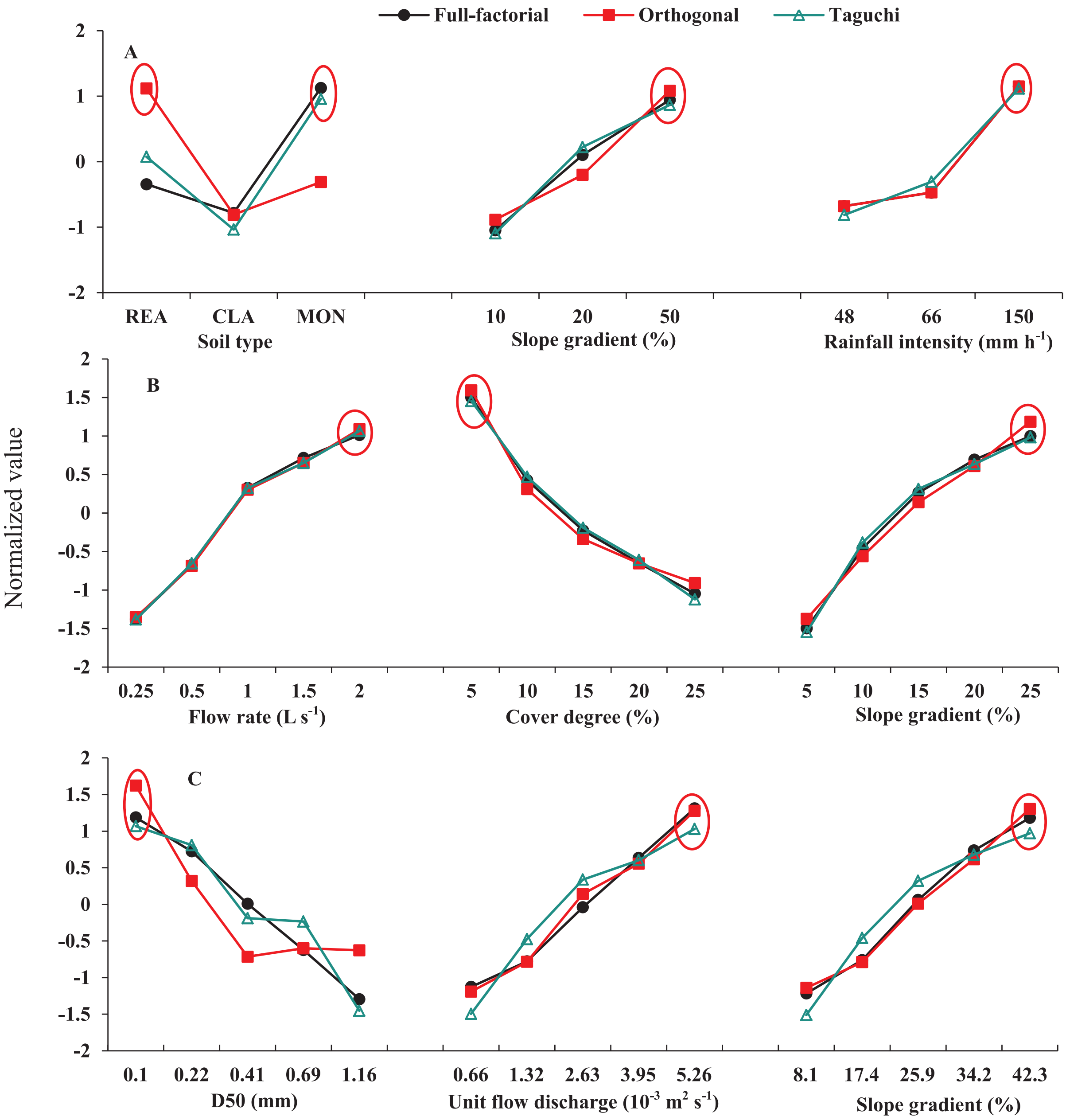

Fig. 4. Main effects of soil type, slope gradient and rainfall intensity for the dependent variable of erosion rate in dataset 4 (A), flow rate, cover degree and slope gradient for the dependent variable of flow velocity in dataset 5 (B), and D_{50}, unit flow discharge and slope gradient for the dependent variable of the transport capacity in dataset 6 (C) obtained from the full-factorial design, orthogonal design and Taguchi method.

full-factorial design, 3 dependent variables from the orthogonal design and 4 dependent variables from the Taguchi method were consistent with the measured maximum value. Although the optimum conditions for most of the dependent variables were different from the conditions of the maximum measured value, the deviations in the values of dependent variables between these two conditions were small for most of the dependent variables. There were only 3 dependent variables with relative differences greater than 10% in comparison to the measured maximum value.

3.4. Significance and contribution of factor

A univariate ANOVA was conducted to explore the effects of factors on the dependent variables using the measured experimental data from both the full-factorial and orthogonal design methods and the S/N ratios from the Taguchi method. Table 4 presents the results of the univariate ANOVA for these three methods for the effects of the different factors on the dependent variables. The effects by each factor on the dependent variables that were identified as statistically significant ($p < 0.05$) included 43 sets for the full-factorial design, 25 sets for the orthogonal design and 37 sets for the Taguchi method. The ranks of the factors for the variations in the dependent variables were obtained according to the PC of each factor from these three methods (Table 4). For the 14 dependent variables, 8 had the same ranks, and 1 had an inconsistent rank obtained from these three methods. There were 13 dependent variables with the same ranks obtained from both the full-factorial design and the Taguchi method and 8 dependent variables with the same ranks obtained from both the full-factorial design and the orthogonal design. The PCs of the error from the Taguchi method for 12 of the dependent variables were the lowest for these three methods.

Table 3

Measured maximum values and measured optimum condition values obtained from different experimental designs for all dependent variables.

Datasets	Variable	Measured max. value	Measured value for optimum conditions		
			FFD	OD	TD
Dataset 1	R	149.38	139.70	139.70	139.70
	D	32.13	32.13	25.82	25.82
	C	249.70	247.32	184.85	184.85
	V	0.52	0.52	0.52	0.52
Dataset 2	R	111.89	110.98	110.98	110.98
	D	14.17	14.17	13.44	13.44
	C	199.39	127.66	121.14	121.14
	V	0.26	0.26	0.25	0.25
Dataset 3	R	107.34	100.32	102.78	100.32
	D	9.29	9.29	8.81	9.29
	C	104.81	96.90	96.90	96.90
Dataset 4	D	11.70	10.91	10.91	10.91
Dataset 5	V	1.04	1.04	1.04	1.04
Dataset 6	Tc	9.53	9.53	9.53	9.53

R, runoff rate (mm h^{-1}); D, erosion rate (kg m^{-2} h^{-1}); C, sediment concentration (kg m^{-3}); V, flow velocity (m s^{-1}); Tc, transport capacity of overland flow (kg m^{-1} s^{-1}); FFD, full-factorial design; OD, orthogonal design; TD, Taguchi design.

3.5. *Prediction based on orthogonal design and Taguchi method*

Adjusted R-squared values are used to explain the degree to which the input independent variables explain the variation of the dependent variable, and they indicated that the predictions of the dependent variables based on the ANOVA were satisfactory for the most cases in this study (Table 4). Fig. 5 presents the scatterplots of the predicted values for the dependent variables obtained from both the orthogonal design and the Taguchi method versus the measured values. The predicted values for the Taguchi method versus the measured values were closer to the 1:1 line than that for the orthogonal design. The evaluating indicators of the predictive power of both the orthogonal design and the Taguchi method are presented in Table 5. The R^2 between the predicted and measured values for all dependent variables ranged from 0.54 to 0.99 and presented an overall mean and standard deviation (SD) of 0.83 ± 0.13 and a coefficient of variation (CV) of 0.16 for the orthogonal design, and the value ranged from 0.61 to 0.99 and presented with an overall mean and SD of 0.90 ± 0.10 and a CV of 0.12 for the Taguchi method. The NSE between the predicted and measured values for all dependent variables ranged from 0.39 to 0.99 and presented an overall mean and SD of 0.79 ± 0.18 and a CV of 0.22 for the orthogonal design, and the value ranged from 0.53 to 0.99 and presented an overall mean and SD of 0.86 ± 0.13 and a CV of 0.15 for the Taguchi method. The RRMSE between the predicted and the measured values for all dependent variables ranged from 0.22 to 0.93 and presented an overall mean and SD of 0.69 ± 0.22 and a CV of 0.32 for the orthogonal design, and the value ranged from 0.47 to 0.94 and presented an overall mean and SD of 0.77 ± 0.16 and a CV of 0.21 for the Taguchi method. The MAPE between the predicted and the measured values for all dependent variables ranged from 5.96% to 1371.01% presented an overall mean and SD of 156.63 ± 358.89% and a CV of 2.29 for the orthogonal design, and the value ranged from 4.94% to 29.71% and presented an overall mean and SD of 15.40 ± 8.64% and a CV of 0.56 for the Taguchi method. The TIC between the predicted and the measured values for all dependent variables ranged from 0.03 to 0.26 and presented an overall mean and SD of 0.12 ± 0.08 and a CV of 0.65 for the orthogonal design, and the value ranged from 0.02 to 0.15 and presented an overall mean and SD of 0.08 ± 0.05 and a CV of 0.62 for the Taguchi method. Although the values of R^2, NSE, RRMSE, MAPE and TIC between the orthogonal and Taguchi methods were relatively close for a few cases (such as runoff rate and flow velocity), these values indicated that the prediction of the Taguchi method was generally better than that of the orthogonal design in most cases, especially for the dependent variable of erosion rate (Table 5). The absolute errors and relative errors between the predicted and measured values were also calculated and analyzed (Figs. 6 and 7). Except for the dependent variable of runoff rate, the values of mean, upper quartile, median and lower quartile of the absolute errors and relative errors for the other dependent variables from the Taguchi method were significantly lower those from the orthogonal design. Regardless of the dependent variables, the values of all relative errors ranged from 0.00% to 56425%, and presented an overall mean and SD of 260.34 ± 1843.65% and a CV of 7.05 for the orthogonal design, and they ranged from 0.01% to 133.66%, and presented with an overall mean and SD of 16.88 ± 18.42% and a CV of 1.09 for the Taguchi method. The number of relative errors less than 100% accounted for 99.67% of the total (1787 out of 1793) for the Taguchi method and 84.89% of the total (1522 out of 1793) for the orthogonal design. In general, the results of the relationships, the absolute errors and the relative errors between the predicted and measured values suggested that the predicted values from the Taguchi method were closer than those from the orthogonal design to the measured values. In addition, there were different effects on prediction for the different dependent variables. The Taguchi method could significantly promote the prediction accuracy of the dependent variable when the prediction accuracy of this dependent variable from the orthogonal design was poor.

4. Discussion

4.1. *Effect of the nonquantifiable factor*

Nonquantifiable factors might lead to the differences in the results from both the full-factorial and orthogonal design methods. In datasets 3 and 4, soil type is a nonquantifiable factor. In the course of the experiment, in addition to small differences in the physical and chemical properties of the same soil type, the processes of packing soil might result also in small differences of soil physical properties among the tests. In addition, determining the sensitivity of different soil types to erosion and runoff production and ranking their appropriate sensitivity levels are difficult before performing experiments. The rank of sensitivity levels would affect the selected representative tests when using the orthogonal/Taguchi design, which may lead to inconsistency in the main effect of soil type on erosion between the full-factorial design and the orthogonal design for datasets 3 and 4. Although the same test combinations were used for the orthogonal design and Taguchi method, the S/N ratio reduced the effect of the error for the Taguchi method and caused the main effect trend and the optimum soil type condition to be in line with the full-factorial design for datasets 3 and 4. This result demonstrated that the Taguchi design is more effective for these tests with nonquantifiable factors, and could produce results closer to the results from a full-factorial design. However, it is still recommended to avoid nonquantifiable factors as much as possible when applying the Taguchi method.

4.2. *Effect of influencing factor and its intervals between adjacent levels*

The influencing factors made different contributions to the variations in the values of the dependent variables. The results obtained from both the orthogonal design and the Taguchi method were consistent with those obtained from the full-factorial design for the factors with greater PCs relative to the variations in the values of the dependent variables (Youssef et al., 1994; Barto and Mach, 2014). The PCs of rainfall intensity to the variations in the values of the different variables were the greatest except for sediment concentration in dataset 2 and flow velocity in datasets 1 and 2. The main effects and optimum conditions of rainfall intensity obtained from these three designs were

Table 4
Significance and percentage contribution of the factors' effects on dependent variables based on ANOVA.

Datasets	Variable	Factor	Full-factorial design				Orthogonal design				Taguchi design			
			A-R^2	DF	Sig.	PC	A-R^2	DF	Sig.	PC	A-R^2	DF	Sig.	PC
Dataset 1	R	L	0.947	3	0.006	0.91	0.964	3	0.252	0.55	0.977	3	0.095	1.08
		SC		3	0.004	0.99		3	0.100	1.63		3	0.056	1.58
		I		3	0.000	92.81		3	0.000	94.24		3	0.000	95.08
		Error		54		5.28		6		3.57		6		2.26
	D	L	0.802	3	0.000	12.80	0.857	3	0.017	19.60	0.948	3	0.003	14.93
		SC		3	0.000	10.19		3	0.014	21.09		3	0.014	7.69
		I		3	0.000	57.24		3	0.003	45.02		3	0.000	72.22
		Error		54		19.77		6		14.29		6		5.16
	C	L	0.781	3	0.000	23.22	0.924	3	0.001	30.04	0.907	3	0.003	26.93
		SC		3	0.000	13.71		3	0.003	23.99		3	0.016	13.20
		I		3	0.000	41.21		3	0.001	38.38		3	0.001	50.62
		Error		54		21.86		6		7.59		6		9.25
	V	L	0.797	3	0.000	59.83	0.757	3	0.006	53.25	0.879	3	0.001	60.80
		SC		3	0.001	5.13		3	0.146	7.87		3	0.192	2.83
		I		3	0.000	14.77		3	0.070	14.59		3	0.007	24.31
		Error		54		20.26		6		24.30		6		12.06
Dataset 2	R	S	0.983	4	0.000	0.64	0.971	4	0.345	0.12	0.991	4	0.021	0.53
		I		4	0.000	92.78		4	0.000	92.67		4	0.000	93.63
		L		4	0.000	4.92		4	0.001	4.34		4	0.000	4.89
		Error		112		1.66		12		2.88		12		0.95
	D	S	0.917	4	0.000	9.26	0.949	4	0.000	9.16	0.954	4	0.000	9.61
		I		4	0.000	79.59		4	0.000	82.74		4	0.000	85.16
		L		4	0.000	2.89		4	0.020	2.95		4	0.183	0.65
		Error		112		8.26		12		5.15		12		4.58
	C	S	0.616	4	0.000	30.99	0.613	4	0.014	25.40	0.694	4	0.003	31.86
		I		4	0.000	7.18		4	0.095	9.89		4	0.029	14.94
		L		4	0.000	23.48		4	0.013	26.01		4	0.010	22.59
		Error		112		38.35		12		38.70		12		30.60
	V	S	0.963	4	0.000	8.91	0.961	4	0.000	6.89	0.938	4	0.002	6.89
		I		4	0.000	32.37		4	0.000	37.75		4	0.000	37.75
		L		4	0.000	55.05		4	0.000	51.46		4	0.000	51.46
		Error		112		3.67		12		3.90		12		3.90
Dataset 3	R	ST	0.992	3	0.000	0.14	0.995	3	0.470	0.01	0.998	3	0.109	0.13
		L		3	0.000	0.17		3	0.560	−0.02		3	0.228	0.05
		S		3	0.259	0.00		3	0.740	−0.05		3	0.420	0.01
		I		3	0.000	98.81		3	0.000	99.60		3	0.000	99.65
		Error		241		0.79		3		0.46		3		0.16
	D	ST	0.785	3	0.000	2.83	0.580	3	0.680	−3.75	0.999	3	0.001	3.44
		L		3	0.001	1.26		3	0.692	−3.95		3	0.003	1.43
		S		3	0.000	8.76		3	0.520	−0.50		3	0.000	8.80
		I		3	0.000	65.91		3	0.053	66.19		3	0.000	86.24
		Error		241		21.47		3		42.01		3		0.10
	C	ST	0.795	3	0.000	5.28	0.218	3	0.922	−13.25	0.999	3	0.000	8.85
		L		3	0.000	3.32		3	0.785	−9.92		3	0.001	4.36
		S		3	0.000	16.92		3	0.472	1.43		3	0.000	23.19
		I		3	0.000	54.23		3	0.152	43.57		3	0.000	63.45
		Error		241		20.53		3		78.17		3		0.15
Dataset 4	D	ST	0.876	2	0.059	2.17	0.897	2	0.490	0.10	0.999	2	0.075	2.67
		S		2	0.007	5.06		2	0.265	4.56		2	0.028	7.82
		I		2	0.000	80.43		2	0.029	85.04		2	0.003	88.56
		Error		20		12.35		2		10.30		2		0.94
Dataset 5	V	FR	0.945	4	0.000	32.67	0.918	4	0.000	27.44	0.994	4	0.000	31.93
		CD		4	0.000	32.10		4	0.000	33.43		4	0.000	29.86
		S		4	0.000	29.69		4	0.000	30.92		4	0.000	37.61
		Error		112		5.54		12		8.22		12		0.60
Dataset 6	Tc	D_{50}	0.831	4	0.000	2.91	0.787	4	0.103	5.15	0.988	4	0.002	1.40
		UFD		4	0.000	43.67		4	0.000	36.94		4	0.000	51.98
		S		4	0.000	36.55		4	0.000	36.61		4	0.000	45.41
		Error		112		16.88		12		21.30		12		1.21

A-R^2, Adjusted-R squared value: DF, degrees of freedom; R, runoff rate (mm h^{-1}); D, erosion rate (kg m^{-2} h^{-1}); C, sediment concentration (kg m^{-3}); V, flow velocity (m s^{-1}); Tc, transport capacity of overland flow (kg m^{-1} s^{-1}); L, slope length (m); SC, percentage of gravel in soil (%); S, slope gradient (%); I, rainfall intensity (mm h^{-1}); ST, soil type; CD, cover degree (%); FR, flow rate (L s^{-1}); UFD, unit flow discharge (m^{-2} s^{-1}); PC, percentage contribution (%).

consistent for all dependent variables in this study except for sediment concentration in dataset 2. These results indicated that the main factors could be identified by these three designs (Youssef et al., 1994; Barto and Mach, 2014). By decreasing the contributions of the influencing factors to the variation of the dependent variables, the probability of obtaining inconsistent results from these three designs increased. However, the probability of obtaining inconsistent results between the orthogonal design and full-factorial design was still higher than that between the full-factorial design and Taguchi design.

The scale of the intervals between adjacent levels of an influencing

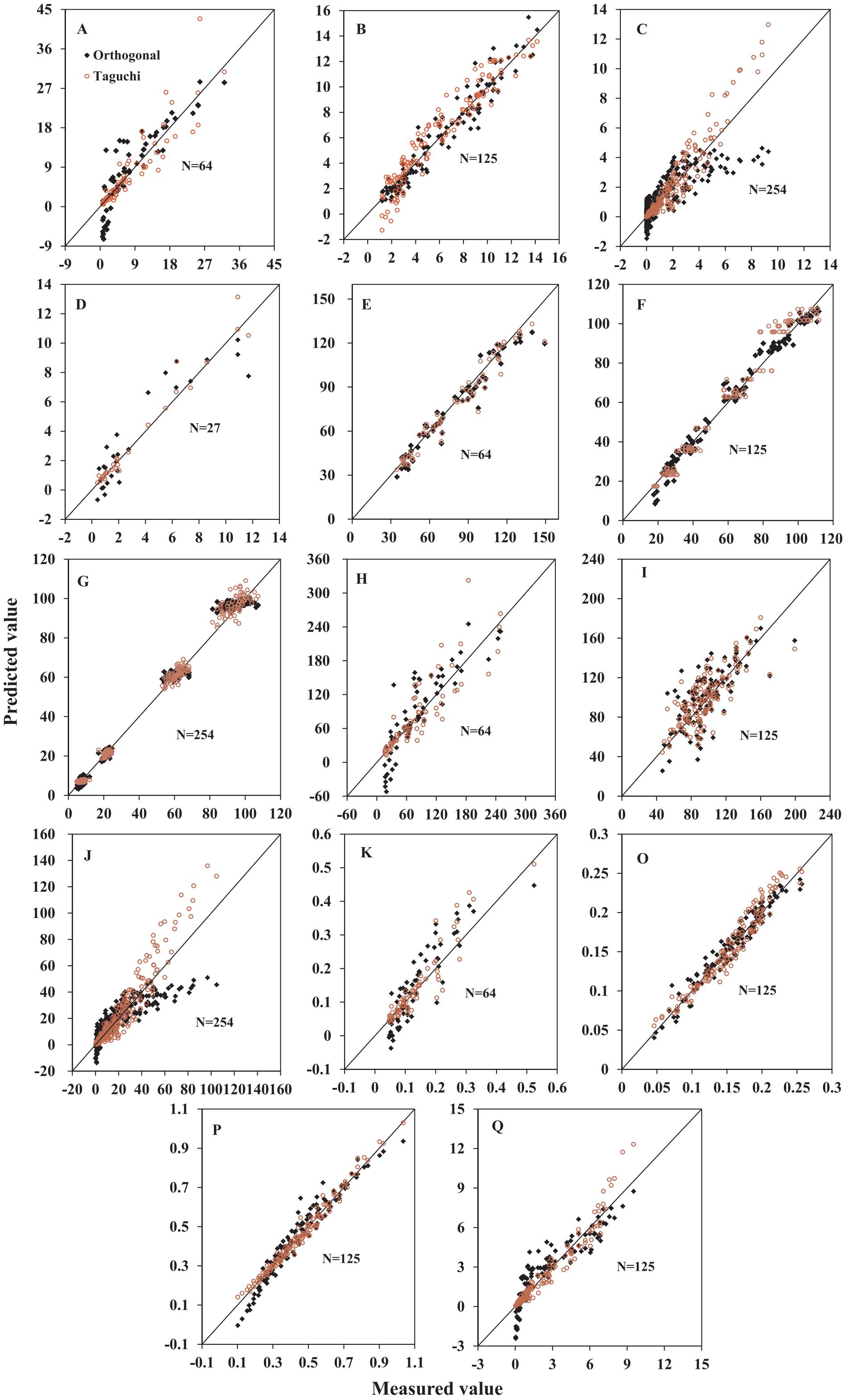

Fig. 5. Measured versus predicted erosion rate (kg m^{-2} h^{-1}) for dataset 1 (A), dataset 2 (B), dataset 3 (C) and dataset 4 (D); measured versus predicted runoff rate (mm h^{-1}) for dataset 1 (E), dataset 2 (F) and dataset 3 (G); measured versus predicted sediment concentration (kg m^{-3}) for dataset 1 (H), dataset 2 (I) and dataset 3 (J); measured versus predicted flow velocity (m s^{-1}) for dataset 1 (K), dataset 2 (O) and dataset 5 (P); measured versus predicted transport capacity (kg m^{-1} s^{-1}) for dataset 6 (Q). All predicted values were obtained from the orthogonal design and Taguchi method.

Table 5
Evaluating indicators of the predictive power of both the orthogonal design and the Taguchi method by ANOVA.

Datasets	Variable	R^2		NSE		RRMSE		MAPE (%)		TIC	
		OD	TD	OD	TD	OD	TD	OD	TD	OD	TD
Dataset 1	R	0.95	0.95	0.94	0.94	0.90	0.91	7.32	6.42	0.05	0.04
	D	0.78	0.83	0.70	0.83	0.49	0.57	148.37	24.71	0.18	0.15
	C	0.77	0.76	0.65	0.71	0.59	0.63	60.24	23.83	0.16	0.15
	V	0.79	0.86	0.61	0.88	0.61	0.71	41.17	16.45	0.15	0.12
Dataset 2	R	0.98	0.97	0.98	0.96	0.93	0.91	7.12	7.77	0.03	0.04
	D	0.91	0.94	0.90	0.93	0.81	0.85	14.06	14.43	0.08	0.07
	C	0.54	0.61	0.39	0.53	0.79	0.82	17.55	14.83	0.10	0.09
	V	0.95	0.94	0.95	0.93	0.93	0.92	5.96	6.83	0.03	0.04
Dataset 3	R	0.99	0.99	0.99	0.99	0.93	0.93	7.69	6.14	0.03	0.03
	D	0.67	0.93	0.66	0.84	0.22	0.47	1371.01	29.71	0.26	0.15
	C	0.71	0.93	0.68	0.78	0.43	0.53	153.55	29.02	0.23	0.15
Dataset 4	D	0.84	0.97	0.70	0.96	0.60	0.80	59.19	12.70	0.14	0.02
Dataset 5	V	0.94	0.98	0.92	0.98	0.89	0.94	11.50	4.94	0.05	0.03
Dataset 6	Tc	0.81	0.94	0.80	0.93	0.56	0.74	288.02	17.83	0.16	0.09

R^2, coefficient of determination; NSE, Nash-Sutcliffe efficiency coefficient; RRMSE, relative root mean squared error; MAPE, mean absolute percentage error (%); TIC, Thiel inequality coefficient; R, runoff rate (mm h^{-1}); D, erosion rate (kg m^{-2} h^{-1}); C, sediment concentration (kg m^{-3}); V, flow velocity (m s^{-1}); Tc, transport capacity of overland flow (kg m^{-1} s^{-1}); OD, orthogonal design; TD, Taguchi design.

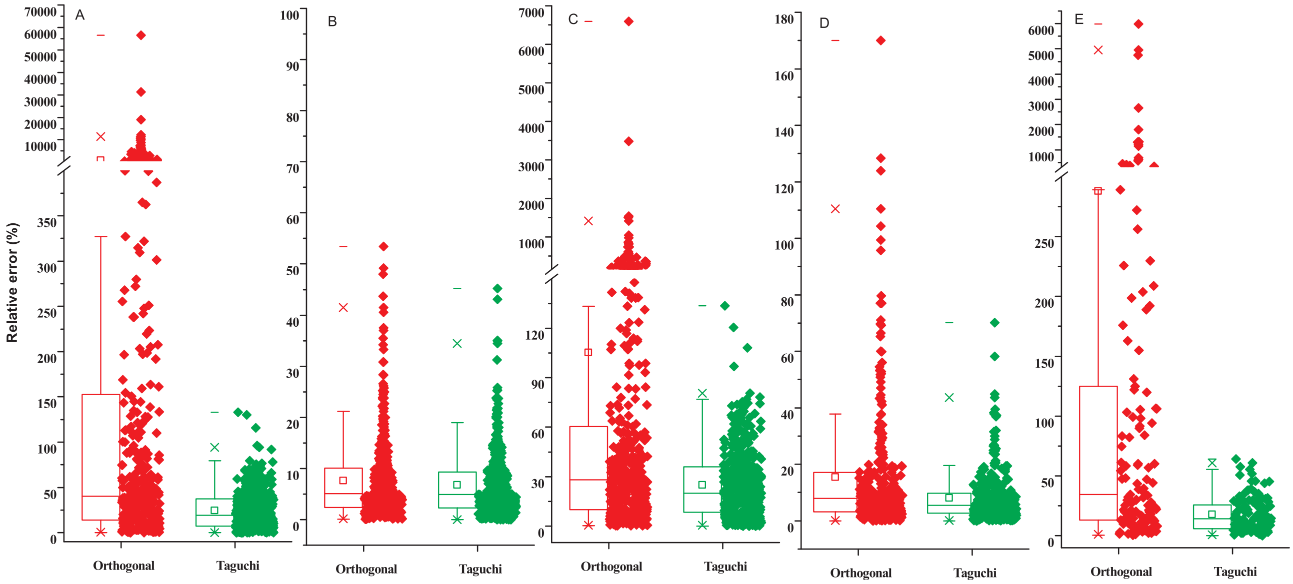

Fig. 6. Relative errors between the measured and predicted values for the dependent variables of erosion rate (A), runoff rate (B), sediment concentration (C), flow velocity (D) and transport capacity (E) obtained from the orthogonal design and Taguchi method.

factor may cause inconsistent results between the full-factorial design and orthogonal design. Intervals that are too small between adjacent levels may result in no obvious variations in the values of the dependent variables among the adjacent levels. The lack of obvious variations in the dependent variables may be masked by experimental errors when using orthogonal and Taguchi designs because of the limited number of experiments, which may cause inconsistencies between the full-factorial design and orthogonal design in terms of the main effects and optimum conditions for the factors. In this study, the intervals among the adjacent slope gradient and slope length levels were too small in dataset 3, which may have caused the inconsistent results obtained from the full-factorial and orthogonal designs in terms of the main effect and optimum conditions for the factors in most cases. For non-quantifiable factors, the intervals between adjacent levels were unclear, which might have caused the differences in the results between the full-factorial and orthogonal designs. In addition, the effects of some factors on the dependent variables exhibited critical inflection points, i.e., non-linear relationships. For example, the critical effects of slope gradient and slope length on the erosion rates were between 47% and 58% and 0.4 m and 1.2 m in dataset 2, respectively. These critical inflection points might have caused the inconsistent results between the full-factorial and orthogonal designs. Compared to the orthogonal design, the Taguchi method could identify the variations in the measured values of the dependent variables when the intervals were too small by reducing the noise in the experiments to obtain results consistent with the results from the full-factorial design in most cases. However, a few cases still presented inconsistent results between the full-factorial design and the Taguchi method. Thus, selecting suitable intervals for the experimental levels of the influencing factors is necessary when applying the Taguchi method to design simulated soil erosion experiments at the slope scale according to the professional knowledge and practical experiences, which would ensure that the true conclusions are obtained from the Taguchi method.

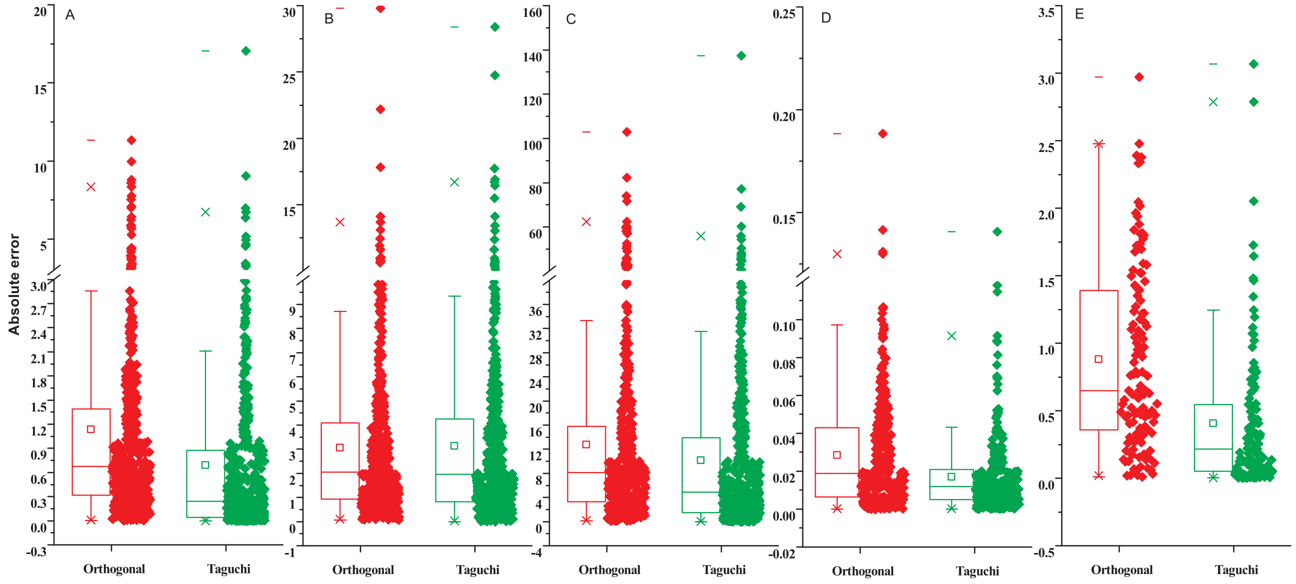

Fig. 7. Absolute errors between the measured and predicted values for the dependent variables of erosion rate (A), runoff rate (B), sediment concentration (C), flow velocity (D) and transport capacity (E) obtained from orthogonal design and Taguchi method.

4.3. *Effects of slope scale and type of experiment*

The scale of the soil box affected the patterns, dynamic processes, amount and complications of soil erosion (Bagio et al., 2017). For small-scale soil boxes, which eliminates the effect of rill erosion, only splash and sheet erosion occurred during rainfall (Kinnell, 2005, 2012; Zhang and Wang, 2017). When the scale of the soil box is increased, splash, sheet, interrill, rill and ephemeral gully erosion might occur simultaneously over the slope (Truman et al., 2001; Rejman and Brodowski, 2005; Han et al., 2019). Meanwhile, rill and ephemeral gully erosion might occur randomly during rainfall (Oygarden, 2003; Di Stefano and Ferro, 2011). These changes would complicate the soil erosion processes on the slope with increasing experimental scale. The effects of the slope scale on soil erosion still need further study. Thus, the scale of the soil box might affect the results from different designs. In this study, the results from the Taguchi method were generally closer than those from the orthogonal design to from the full-factorial design for all datasets with different experimental scales. However, the Taguchi method presented better results for the experiments with small-scale slopes than large-scale slopes. The experimental scale of dataset 1 was the largest in this study. In general, the R^2, NSE and RRMSE values between the predicted values obtained from the Taguchi method and the measured values for erosion rate, runoff rate and flow velocity were lower for dataset 1 than for the other datasets with simulated rainfall. In contrast, datasets 2, 3 and 4, which had a smaller scale of slope than dataset 1, generally demonstrated better results than dataset 1.

In addition, the type of experiment might affect the results from the orthogonal design and the Taguchi method. Simulated flow experiments are simpler and easier to control than simulated rainfall experiments. The differences in the results from the orthogonal design and Taguchi method for dataset 5 and dataset 6 were smaller than those for the other datasets that were produced from the simulated rainfall experiments. The trends of the main effects of the influencing factors and the optimum conditions were almost the same for the orthogonal design and Taguchi method for dataset 5 and dataset 6. Thus, the Taguchi method may be more useful for more complex experiments.

4.4. *Effects of dependent variables*

The consistency of the results obtained from the orthogonal design and the Taguchi method was different for the different dependent variables. This consistency was determined by the contribution of factors to dependent variables. The variations in runoff rates were basically controlled by rainfall intensity. The contribution of rainfall intensity to the variations in runoff rates was more than 90% for all datasets referring to runoff rate. The other factors had a trifling effect on runoff production. Under this circumstance, no obvious differences were found in the results from the orthogonal design and Taguchi method, and their results were close to those from the full-factorial design, especially for the prediction. The evaluating indicator values (R^2, NSE RRMSE, MAPE and TIC), the absolute errors and the relative errors were almost the same for both methods (Figs. 5–7). In general, the smaller the PC of the factor is to the dependent variable, the more likely it is that there will be inconsistencies in the analysis of the main effect trend and the optimum conditions. These differences were attributed to the small differences in the dependent variable between the two levels. For dataset 6, the PC of particle median size to transport capacity was much lower than that of unit flow discharge and slope gradient, both of which had similar PCs (Table 4). The results obtained from the orthogonal design and Taguchi method for particle median size were inconsistent for the main effect trend analysis. When all factors had a similar contribution rate to the dependent variable, these three designs were more likely to obtain consistent results. For dataset 5, the differences in the PCs of flow rate, slope gradient and cover degree were small. The results of the main effect trend and the optimum conditions obtained from these three methods were consistent. The predicted values were close to the measured values. For the two methods, the R^2, NSE and RRMSE values were greater than 0.90 and the values of MAPE and TIC were closer. For the dependent variables, such as erosion rate, which exhibited complicated responses to influencing factors, the Taguchi method could produce better conclusions than the orthogonal design. For the dependent variable of sediment concentration, the probability of obtaining inconsistent results from these three methods was greater than that for the other dependent variables. The R^2, NSE and RRMSE values were relatively low, and the differences in the R^2, NSE and RRMSE between the orthogonal design and Taguchi method were small. These results might be attributed to the fact that sediment concentration, which is calculated from runoff and erosion rate, is a composite indicator whose variations reflect variations in runoff and soil loss.

5. Conclusions

The Taguchi method is a reliable and economical method to study soil erosion on the slope scale. In this study, the orthogonal design was used as an additional design to prove the merits of the Taguchi method. Both the orthogonal design and Taguchi methods could significantly reduce the number of tests. The values of the common statistical parameters for the dependent variables obtained from orthogonal/ Taguchi designs could closely represent those obtained from a full-factorial design. In terms of the main effect, significance and PC of each factor, optimum conditions and prediction for the dependent variables, the study indicates that the results obtained from the Taguchi method were much closer than those obtained from orthogonal design to the results from a full-factorial design at the slope scale. The Taguchi method presented better results for dependent variables with complex variations and at the small-scale slope than at the large-scale slope, and it may be more useful for more complex experiments. In general, the Taguchi method is superior to an orthogonal design. Based on a comparison among the results from the full-factorial design, orthogonal design and Taguchi method, we can conclude that the Taguchi method could, to some extent, act as a substitute for the full-factorial design and obtain reliable experimental conclusions without losing valuable information for simulated soil erosion experiments on the slope scale. However, although the Taguchi method could reduce the effects of experimental error on the results by analyzing the S/N ratio and obtaining better results than the orthogonal design, the results from the Taguchi method would be affected by nonquantifiable factors, the intervals between adjacent levels of a factor, the size of the soil box and the type of dependent variables. Differences in the results from both the full-factorial design and Taguchi methods still existed for some cases. Thus, the professional knowledge and practical experiences of soil erosion are required to determine the dependent variables, the factors and their levels when using the Taguchi method to design simulated soil erosion experiments on the slope scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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