Applicability of WEPP Sediment Transport Equation to Steep Slopes

G. H. Zhang, B. Y. Liu, X. C. Zhang

Abstract: This study was carried out to evaluate the transport capacity equations of the Yalin equation and the WEPP model for steep slopes, and to recommend the best-fitting exponent value of shear stress in the WEPP transport capacity equation. The transport capacity was measured in a 5 m long, 0.4 m wide hydraulic flume, and the diameter of test sediment varied from 20 to 2000 μm with a median diameter of 280 μm. Flow discharge ranged from 0.625 × 10^{-3} to 5 × 10^{-3} m^2 s^{-1}, and slope gradient ranged from 8.8% to 46.6%. An averaged dimensionless critical shear stress of 0.052 was used for \( T_c \) calculation in the Yalin equation. The relationship between transport coefficient \( K_t \) and shear stress was graphically determined for the transport capacity of the WEPP model. The transport capacities predicted by the Yalin equation and the WEPP model were compared with the measured \( T_c \) to qualify their suitability on steep slopes. The results showed that the Yalin equation overestimated the measured \( T_c \) by 109%. The error increased as a power function of shear stress \( (r^2 = 0.98) \). The transport capacity of the WEPP model underestimated the measured \( T_c \) by 65%. The absolute error increased as a linear function of shear stress \( (r^2 = 0.99) \). Paired t-tests showed that the transport capacities calculated using the Yalin equation and the WEPP equations were different significantly from measured \( T_c \) at the 0.05 level. Sediment transport coefficient \( K_t \), calculated with the WEPP equation overestimated the measured \( T_c \) by 109%. The error increased as a power function \( (r^2 = 0.97) \).

Keywords. Sediment transport capacity, Soil erosion, Steep slopes, WEPP model, Yalin equation.

The need to develop physically based soil erosion models (Nearing et al., 1989; De Roo et al., 1996; Morgan et al., 1998) and to describe the distributed processes of detachment, transport, and deposition has stimulated researchers to establish the best equations for estimating overland flow transport capacity \( (T_c) \) (Foster and Meyer, 1972; Finkner et al., 1989; Govers, 1990; Ferro, 1998; Hessel and Jetten, 2007). Sediment transport capacity, which is the maximum amount of sediment that a flow can transport (Huang et al., 1999; Li and Abrahams, 1999), is the basic concept for determining detachment and deposition processes in current process-based erosion models. A precise prediction of sediment transport capacity is imperative for improving the accuracy of detachment and deposition simulation (Ahmandi et al., 2006; Hessel and Jetten, 2007).

Most sediment transport equations were developed under typical hydraulic conditions of rivers and channels (Ferro, 1998). The Yalin equation (Yalin, 1963) has been widely used in soil erosion models (Finkner et al., 1989; Nearing et al., 1989; Bulygina et al., 2007; Hessel and Jetten, 2007) and can be written as:

\[
\frac{T_c}{SGd} = 0.635\delta \left[ 1 - \frac{1}{\beta} \left( 1 + \beta \right) \right] \tag{1}
\]

\[
\tau = \rho g RS \tag{2}
\]

\[
\delta = \frac{Y}{Y_c} - 1 \quad \text{(when} \ Y < Y_c, \ \delta = 0) \tag{3}
\]

\[
\beta = 2.45 \left( SG \right)^{0.4} Y_c^{0.5} \delta \tag{4}
\]

\[
Y = \frac{RS}{(SG - 1)gh} \tag{5}
\]

where \( T_c \) is the sediment transport capacity \( \left( \text{kg m}^{-1} \text{s}^{-1} \right) \), \( SG \) is the particle specific gravity \( \left( \text{unitless} \right) \), \( d \) is the particle diameter \( \left( \text{m} \right) \), \( g \) is the acceleration due to gravity \( \left( \text{m s}^{-2} \right) \), \( \rho \) is the water density \( \left( \text{kg m}^{-3} \right) \), \( \tau \) is the shear stress of flow \( \left( \text{Pa} \right), R \) is the hydraulic radius \( \left( \text{m} \right), S \) is the slope \( \left( \text{m} \text{m}^{-1} \right) \), \( Y \) is the dimensionless shear stress, \( Y_c \) is the dimensionless critical shear stress from the Shields diagram, and \( \delta \) and \( \beta \) are dimensionless parameters as defined in equations 3 and 4, respectively.

Based on the study of Meyer and Wischmeier (1969), Foster and Meyer (1972) suggested that the Yalin equation (1963)
could be used as a transport capacity equation for overland flow. Alonso et al. (1981) evaluated nine commonly used transport capacity equations against laboratory and field data. The transport formulas were selected for their particular applicability to hydrologic modeling and the data covered in agricultural watersheds. The results indicated that the Yalin equation was the most suitable transport capacity equation for overland flow. Flow shear stress acting on soil is a derived parameter that incorporates the effects of both slope and flow depth. Therefore, shear stress would appear to be the single most significant parameter for a simplified transport capacity equation (Finkner et al., 1989). The following equation, useful both for deriving closed-form solutions of steady-state erosion equations and for reducing the computational time required for the numerical solution of the unsteady continuity equation for sediment routing, was incorporated into the erosion components of the WEPP model in lieu of the full Yalin equation for sediment transport capacity estimation (Finkner et al., 1989; Nearing et al., 1989; Flanagan et al., 2007):

\[ T_c = K_t \tau^{3/2} \]  

where \( K_t \) is the sediment transport coefficient. Since no methods exist for determining \( K_t \) directly, transport coefficient \( K_t \) was evaluated indirectly as (Ferro, 1998; Finkner et al., 1989):

\[ K_t = \frac{T_{c0}}{\tau_0^{3/2}} \]  

where \( T_{c0} \) is the transport capacity computed by the Yalin equation using \( \tau_0 \) of the representative slope, and \( \tau_0 \) is the representative shear stress identified from a particular shape of the profile.

The best agreement between the Yalin equation and equation 6 was obtained using the dual slope transport coefficient (Finkner et al., 1989). This specific transport coefficient was calculated using equation 7 and a reference shear stress equal to the average of the shear stresses acting on the soil at the end of the constant slope reference profiles and at the end of the actual profile (fig. 1). The results also indicated that transport coefficient \( K_t \) was varied with shear stress (fig. 2). But no definite relationship was presented to compute transport coefficient \( K_t \). Owing to this limitation, the WEPP transport equation of the Yalin equation for transport capacity prediction on some occasions (Bulygina et al., 2007).

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MATERIALS AND METHODS

EXPERIMENTAL SETUP

Experiments were carried out in a 5 m long, 0.4 m wide hydraulic flume. The elevation of the top end of flume was adjusted by a stepping motor, allowing the flume bed to be adjusted up to 60%. The test sediment was glued on the surface of the flume bed so that the hydraulic roughness was similar to that of a natural land surface, and the roughness remained constant during the experiments. Two sediment sources were designed to ensure that sediment transport capacity was reached for each combination of flow rate and slope gradient. A 1 m³ hopper was installed over the flume at a distance of 0.5 m from the top. The feed rate of the test sediment was controlled by the rotating speed of rotors installed within the hopper and calibrated to measured data. The rotating speed of the rotors could be adjusted manually by the speed of the drive motor using a portable dial according to the sediment transported by flowing water. The feed rate from the hopper for each combination of flow discharge and slope gradient was adjusted at the beginning of each test and then fixed during the experiment. Another sediment source was a 20 cm wide slot across the flume bed located 0.5 m above the lower end of the flume. The slot was filled with test sediment and covered with a very thin iron sheet, which was glued to the sediment with Vaseline to prevent water drainage during measurements of hydraulic characteristics of flow.

MEASUREMENT OF HYDRAULICS AND TRANSPORT CAPACITY

Test sediment was collected from the bed of the Yongding River near Beijing, China. The diameter of test sediment varied within the range of 20 to 2000 μm with a median diameter of 280 μm. The specific gravity (SG) of the test sediment was 2.4. The test sediment was air-dried and sieved. Particles less than 2 mm were used as test material.

The flow rate was controlled by a series of valves and measured directly by a calibrated flowmeter. Before the experiments, the flume bed slope and flow discharge were adjusted to designed values. Flow depths were measured by a level probe to an accuracy of 0.3 mm. Flow depths were measured by a level probe to an accuracy of 0.3 mm. For stable, measurements of flow depth were made. Flow depths adjusted to designed values, and when the flow became steady, measurements of flow depth were made. Flow depths were measured by a level probe to an accuracy of 0.3 mm. For each combination of flow discharge and slope gradient, 12 depths were measured. One maximum and one minimum flow depth were eliminated from the dataset. The average of the remaining ten depths was considered the mean flow depth for that combination of flow rate and slope gradient. Velocity of flow was measured by fluorescent dye technique in which the velocity of the leading edge of dye was multiplied by a reduction factor of 0.8 to obtain mean velocity (Luk and Merz, 1992).

After the hydraulic measurements, the hopper started to feed sediment to the flow, and the iron sheet was removed immediately afterwards. A thin iron rod was used to stir up any deposition formed under the hopper during the experiments. Five samples were collected and allowed to settle for 24 h. Then the clear water was decanted from the container. The remaining wet sediment was oven-dried at 105°C for 12 h. The dry sediment weight was divided by sampling time and the flume width to obtain sediment transport capacity. The average of five samples was used as the measured sediment transport capacity for that combination of flow discharge and slope gradient. A series of 64 combinations of flow rates (0.625, 1.250, 1.875, 2.500, 3.125, 3.750, 4.375, and 5.000 × 10⁻³ m² s⁻¹) and flume bed slopes (8.8%, 17.6%, 22.2%, 26.8%, 31.5%, 36.4%, 41.4%, and 46.6%) was used.

EVALUATION PROCEDURE

The dimensionless critical shear stress (Yc) is a function of sediment size and velocity. Theoretically, different Yc values should be given for each combination of flow discharge and slope gradient. However, this was difficult to obtain because the range of Yc values was very narrow. Therefore, the average of the minimum and maximum values was used in this study. The transport capacity was predicted by the Yalin equation and compared with the measured data. The sediment transport coefficient was determined graphically from figure 2 to develop the relationship between Kt and shear stress for the transport capacity equation of the WEPP model. The transport capacity calculated by the WEPP model was also compared with observations. Paired t-tests were used to compare the predicted transport capacity from the Yalin equation and the WEPP model against the measured value. For the dataset used in this study, transport coefficient Kt was calculated with the WEPP transport capacity equation using the measured transport capacity as follows (Finkner et al., 1989):

\[ K_t = \frac{T_{cm}}{T_1^{3/2}} \]  

where Tcm is measured transport capacity (kg m⁻¹ s⁻¹). The relationship between calculated transport coefficient and shear stress was analyzed to obtain a steady value of the transport coefficient. The mean absolute error (MAE), relative root mean square error (RMSE), maximum error (ME), relative error (RE), Nash-Sutcliffe efficiency coefficient (NSE), and coefficient of determination (r²) were used to quantify the performance of the Yalin equation, the transport capacity equation of the WEPP model, and a regression equation in this study.

RESULTS AND DISCUSSION

Since the transport capacity equation in the WEPP model is an approximation of the Yalin equation (Finkner et al., 1989), the measured transport capacity was first compared with the transport capacity predicted by the Yalin equation. The minimum and maximum values of the dimensionless critical shear stress (Yc) were 0.050 and 0.054, respectively. The average of 0.052 was used in the Yalin equation. As shown in table 1 and figure 3, the Yalin transport capacity was greater than the measured Tc. The mean relative error of 108.9% was much greater than 10%, which was the criterion used to simplify the Yalin equation for the WEPP model (Finkner et al., 1989). A negative NSE value indicated that the Yalin equation produced poorer results than the measured mean Tc. Paired t-tests showed that the transport capacity calculated using the Yalin equation was significantly different from the measured Tc at the 0.05 level. This result indicated that the Yalin equation might not be suitable for steep slope conditions. Hessel and Jetten (2007) reported that the Yalin equation was too sensitive to slope gradient. A greater coefficient of determination (0.97) indicated that a systematic bias existed between the observed and Yalin
Table 1. Comparison between predicted and measured \( T_c \),[a]

<table>
<thead>
<tr>
<th></th>
<th>MAE (kg m(^{-1}) s(^{-1}))</th>
<th>RRMSE</th>
<th>ME (kg m(^{-1}) s(^{-1}))</th>
<th>RE (%)</th>
<th>NSE</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yalin</td>
<td>2.98</td>
<td>1.05</td>
<td>7.11</td>
<td>46.5 to 264.9</td>
<td>-0.93</td>
<td>0.97</td>
</tr>
<tr>
<td>WEPP</td>
<td>2.22</td>
<td>0.84</td>
<td>-6.48</td>
<td>-75.3 to -42.8</td>
<td>-0.24</td>
<td>0.97</td>
</tr>
<tr>
<td>( T_c = 0.053 \tau^{0.31} )</td>
<td>0.31</td>
<td>0.13</td>
<td>1.07</td>
<td>-33.9 to 27.8</td>
<td>0.97</td>
<td>0.97</td>
</tr>
</tbody>
</table>

[a] MAE = mean absolute error, RRMSE = relative root mean square error, ME = maximum error, RE = relative error, NSE = Nash-Sutcliffe efficiency coefficient.

Figure 3. Comparison between measured \( T_c \) and \( T_c \) predicted by Yalin equation.

Figure 4. Absolute error as a function of shear stress (Yalin equation).

\( T_c \) values. As shown in figure 4, the absolute error increased as shear stress increased. The best-fitting equation between shear stress and absolute error was a simple power function (fig. 4):

\[
AE_{Yalin} = 0.120 \tau^{1.594} \quad (r^2 = 0.96)
\]  

where \( AE_{Yalin} \) is the absolute error predicted by the Yalin equation (kg m\(^{-1}\) s\(^{-1}\)). A close relationship between shear stress and absolute error indicated that \( AE_{Yalin} \) was related to both slope gradient and flow discharge.

In the transport capacity equation of the WEPP model, transport coefficient \( K_t \) is a function of shear stress. Analysis with data derived graphically from figure 2 indicated that transport coefficient \( K_t \) increased as a simple power function of shear stress:

\[
K_t = 0.025 \tau^{0.364} \quad (r^2 = 0.97)
\]

This result indicated that part of the effect of shear stress on transport capacity is included in the transport coefficient \( K_t \) in the WEPP model. Substituting equation 10 into the WEPP \( T_c \) equation yields:

\[
T_c = K_t \tau^{3/2} = 0.025 \tau^{0.364} \tau^{3/2} = 0.025 \tau^{1.864}
\]

Equation 11 shows that for a typical silt loam soil, the transport capacity of the WEPP model increases as a power function of shear stress. The exponent of 1.864 is less than the value of 2 reported by Trout (1999). The fitted coefficient of 0.025 was not correlated to flow hydraulics but probably related to sediment properties (Yalin, 1963; Govers, 1990). In the study of Finkner et al. (1989), a typical silt loam soil was considered, while sediment with a median diameter of 280 \( \mu \)m was used in this study. The difference in transport capacity may be caused by the different properties of the sediment. However, the performance of the transport capacity equation of WEPP still needs to be evaluated using the measured data of this study.

The transport capacity of the WEPP model underestimated the measured data by 64.5\% (table 1 and fig. 5). Compared with the Yalin equation, the \( T_c \) predicted by the WEPP model was improved since it had lower values of mean absolute error, relative root mean square error, maximum error, and relative error. However, the NSE value of -0.24 indicated that the transport capacity equation of WEPP produced poorer results than the measured mean \( T_c \). Paired t-tests revealed that the transport capacity calculated by the WEPP transport equation was also significantly different from the measured \( T_c \) at the 0.05 level. The predicted error increased as a linear function of shear stress (fig. 6):

\[
AE_{WEPP} = -0.527\tau + 1.544 \quad (r^2 = 0.91)
\]

where \( AE_{WEPP} \) is the absolute error predicted by the WEPP model (kg m\(^{-1}\) s\(^{-1}\)).

For this study, the measured transport capacity increased as shear stress increased. The best-fitting equation for the measured data was a power function (fig. 7):

\[
T_c = 0.054 \tau^{1.982} \quad (r^2 = 0.98)
\]

As shown by equation 13, the measured transport capacity was predicted by shear stress satisfactorily with a coefficient...
of determination of 0.98. The NSE was 0.97. Comparing equation 13 with the transport capacity equation of the WEPP model (Finkner et al., 1989), the exponential value 1.982 was greater than WEPP’s 1.5 by 32% and was very closely to 2 as reported by Trout (1999) for irrigated bean. Comparing equation 13 with equation 11, the exponential value 1.982 was greater than 1.864 by 6%. The coefficient of 0.054 was a little greater than the 0.048 reported by Zhang et al. (2005) and greater than the average value of 0.038 for irrigated bean reported by Trout (1999). It was twice the coefficient of 0.025 in equation 11.

Transport coefficient $K_t$, calculated using measured transport capacity and shear stress (eq. 8), is shown in figure 8 for the 64 combinations of flow discharge and slope gradient. It is clear that transport coefficient $K_t$ varied as a function of shear stress. At large values of shear stress, the transport coefficient became relatively constant. However, $K_t$ decreased rapidly when the shear stress was small. This varying trend in transport coefficient with shear stress is similar to that described by Finkner et al. (1989), although the transport coefficient in this study was much greater.

Further analysis indicated that the relationship between transport coefficient $K_t$ and shear stress $\tau$ was unstable when different exponents of shear stress were used, as shown in figures 8 and 9. If the original 3/2 in the transport capacity equation of the WEPP model was replaced by the fitted exponent 4/2, the calculated transport coefficient fluctuated within a small range as shear stress increased, especially when shear stress was greater than 3 Pa (fig. 9). The maximum, minimum, and average values of $K_t$ decreased as the exponent of shear stress increased from 3/2 to 4/2. The standard deviation also decreased as the exponent of shear stress increased (table 2). This indicated that the effect of shear stress on transport capacity increased and the contribution of transport coefficient $K_t$ decreased as the exponent of shear stress increased. The results of this study indicated that transport capacity was predicted satisfactorily by the WEPP transport capacity equation if the original
exponent of 3/2 for shear stress was replaced by a fitted value of 2. The transport coefficient value of 0.053 was stable and independent of shear stress.

CONCLUSION

In this study, the transport capacity of the Yalin equation and the WEPP model were evaluated by measured transport capacity obtained under a wide range of hydraulic conditions in a 5 m long, 0.4 m wide flume. The results showed that the Yalin equation overestimated the measured transport capacity, and the relative error varied from 46.5% to 264.9%. The absolute error increased as a power function of shear stress \( r^2 = 0.97 \). Transport coefficient \( K_t \) in the transport capacity equation of the WEPP model increased as a power function of shear stress. The WEPP model underestimated transport capacity, and the relative error ranged from -75.3% to -42.8%. The absolute error increased as a linear function of shear stress. The transport coefficient \( K_t \) in this study was fitted by a power function of shear stress satisfactorily \( r^2 = 0.91 \). The measured transport capacity in this study was fitted by a power function of shear stress satisfactorily \( r^2 = 0.98 \). Transport coefficient \( K_t \) varied with shear stress for the WEPP equation; however, \( K_t \) became a constant of 0.053 and was independent of shear stress when the best-fitted exponent of 2 for shear stress was used in lieu of 3/2 of the WEPP equation. The new \( T_c \) equation seems preferred for use in estimating \( T_c \) for steep slopes. However, more studies using fine particles or real soil materials are needed to evaluate the WEPP transport capacity equation as well as this new equation on steep slopes.

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