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A hillslope version of the revised Morgan, Morgan and Finney water erosion model

Geert Sterk

Department of Physical Geography, Utrecht University, PO Box 80.115, NL-3508 TC, Utrecht, the Netherlands

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ABSTRACT

The revised Morgan, Morgan and Finney (rMMF) water erosion model calculates annual surface runoff and soil loss from field-sized areas. The original version of the rMMF is neither suited to calculate water erosion along irregular hillslopes, nor capable to allow infiltration of once generated surface runoff at places where the runoff speed slows down, and infiltration could occur under natural conditions. The aim of this article is to describe a new hillslope version of the rMMF model that allows infiltration of surface runoff, and to show examples of soil erosion modelling along real and hypothetical hillslopes. The new hillslope version (hMMF) splits the entire hillslope into a number of sections that have individual properties, such as slope angle, slope length, soil properties and vegetation characteristics. The surface runoff along the slope is calculated by summing the volume of surface runoff generated in a particular section with the surface runoff coming from the immediate upslope section. The related sediment transport is calculated for each section using the calculated detachment for the section, the sediment coming from the upslope section and the transport capacity. A new variable is introduced to account for infiltration of surface runoff and allows simulating the effects of soil and water conservation structures on water erosion. The model was tested using measured data from plots in Africa, Asia, the US and Europe, as well as for a surveyed hillslope in Tunisia (Barbara watershed). Overall, the performance of the hMMF was reasonable for surface runoff and poor for soil loss when recommended input variable values are used. Calibration of the model resulted in a good performance, which shows the capability of the hMMF model to reproduce measured surface runoff and erosion amounts. In addition, realistic water erosion patterns on hillslopes with soil and water conservation can be simulated.

1. Introduction

Water erosion is globally the most widespread soil degradation problem (Oldeman et al., 1991), with 15.4% of the total land area being affected by moderate to very high erosion rates (Borrelli et al., 2017). Scientific efforts to better understand erosion processes and develop control techniques started already in the 1930's (Bennett, 1939). The first equations to quantify amounts of erosion as a function of terrain characteristics are from the 1940's (Zingg, 1940; Musgrave, 1947), which eventually culminated in the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978). The USLE is a fully empirical soil erosion model that calculates annual soil losses by multiplying six factors: the rainfall erosivity factor (R), the soil erodibility factor (K), the slope length factor (L), the slope steepness factor (S), the crop management factor (C) and the erosion-control practice factor (P) (Wischmeier & Smith, 1978).

The empiricism of the USLE and its specific database from which it was developed has generated criticism. Morgan (2005) and others argued that the USLE is not universal at all, and that the multiplication of six factors cannot adequately describe water erosion. Many water erosion models have been developed since the publication of the USLE. These models vary from deterministic, e.g. the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989; Flanagan & Nearing, 1995), to fully empirical, e.g. Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) and AGricultural Non-Point Source Pollution Model (AGNPS) (Young et al., 1989). An intermediate water erosion model is the Morgan, Morgan and Finney model (Morgan et al., 1984), which can be classified as a semi-empirical model. It retained the simplicity of the USLE but has a stronger physical base. The model was revised by

E-mail address: g.sterk@uu.nl.

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Morgan (2001) and since then is known as the revised Morgan, Morgan and Finney (rMMF) model.

The rMMF model separates the water erosion processes in a water phase and a sediment phase. The water phase calculates the amount of rainfall energy and the surface runoff volume. The sediment phase calculates the amounts of splash detachment, the surface runoff detachment, and the transport capacity of the surface runoff. The final outcome of the model is an annual soil loss from a field sized area on a hillslope (Morgan, 2005). It only accounts for splash erosion, interrill erosion and rill erosion processes; gully erosion is not part of the model. The rMMF model uses 12 equations and requires 15 input variables. Three input variables are rainfall related, five are soil related, six are land cover related and one variable accounts for the slope angle. Morgan (2001) tested the rMMF by comparing model predictions with measured amounts of surface runoff and soil loss on 67 sites. The rMMF model performed reasonably well, but the surface runoff predictions were poor for situations where erosion control measures were implemented. Several other studies reported satisfactory results in different countries. For instance, the model was successfully used in Hungary (Hudek et al., 2014), Kenya (Vigiak et al., 2005) and Spain (Fernandez et al., 2010; Lopez-Vicente et al., 2008).

The rMMF model has at least two limitations that reduce its applicability. First, the model was developed for uniform areas with a linear slope. But hillslopes often have irregular slope profiles and also spatially variable soil and vegetation characteristics. These spatial heterogeneities influence water erosion processes, but the rMMF is not able to capture this. The second issue is infiltration of once generated surface runoff, which can occur on a natural hillslope. For instance, for a concave slope, the slope steepness towards the end of the slope is decreasing. This smaller slope angle will slow down the speed of the surface runoff, and water gets more time to infiltrate (Van de Giesen et al., 2000). The surface runoff infiltration process should not be ignored in the simulation of hillslope hydrology (Vigiak et al., 2006). Indeed, measurements of hillslope surface runoff generally have shown a tendency of decreasing runoff coefficients with increasing slope length (Sheridan et al., 2014). One of the main reasons for this decrease in runoff coefficients with slope length is due to infiltration of surface runoff in areas downslope (Langhans et al., 2014). Moreover, when soil and water conservation measures are present in the field, the original rMMF can only incorporate the effects of such measures through the USLE *P* factor. Actual simulations of the influence of the measures on surface runoff and sediment transport are not possible, because the original model does not allow infiltration of once generated surface runoff. But when grass strips, bench terraces or other soil and water conservation (SWC) measures are implemented on a hillslope, these structures will cause infiltration of surface runoff and reduce its transport capacity. This will result in deposition of sediment, which is also not accounted for in the original rMMF.

Since its publication by Morgan in 2001, several modifications to the original rMMF have been published. These modifications of the rMMF model have usually introduced a number of new variables and equations. For instance, Morgan and Duzant (2008) made changes to the original rMMF model to incorporate effects of vegetation characteristics and soil texture on erosion and deposition processes. The changes comprised 41 new equations and 11 new variables. Likewise, Choi et al. (2017) modified further the Morgan and Duzant (2008) rMMF version to make it applicable at daily time scale. They developed 45 new equations and 18 new variables to make the model suitable for areas with seasonal climates and complex surface configurations. Finally, Shrestha and Jetten (2018) also developed a model version that enables daily-based simulation of soil erosion. They introduced 16 new equations and an equal number of new variables to better account for vegetation dynamics and extreme rain storms in soil erosion processes.

This article presents a new hillslope version of the rMMF model, the hMMF model, that 1) can simulate erosion processes along an irregular hillslope profile, and 2) allows infiltration of surface runoff. The adaptations to the rMMF model are mainly changes of the original field scale rMMF equations, while only two new variables are introduced. It was attempted to retain the simplicity of the rMMF as much as possible. The spatial scale of the hMMF model is the hillslope, and the temporal scale is annual. The aim of this article is to describe the new equations and calculation scheme for the hMMF model, evaluate the model against measured values, and show examples of soil erosion modelling along hillslopes with and without SWC measures.

2. Model description

2.1. The field-scale rMMF model

The following summarizes the main rMMF equations used to calculate annual soil erosion at field-scale as described by Morgan (2001; 2005).

The rainfall kinetic energy (*KE*; J m^{-2}) is a function of the effective rainfall (P_e; mm), i.e. the fraction of mean annual rainfall (*P*; mm) that is not intercepted by the vegetation canopy (*A*; fraction between 0 and 1):

$$P_e = P(1 - A) \tag{1}$$

The effective rainfall is split into direct throughfall (*DT*; mm), which directly reaches the soil, and leaf drainage (*LD*; mm), which is intercepted by the canopy and reaches the surface by stem flow or dripping from leaves. *LD* is a function of the canopy cover (*CC*; fraction between 0 and 1):

$$\mathrm{LD} = P_e \mathrm{CC} \tag{2}$$

And the remaining part of the effective rainfall is thus direct throughfall:

$$\mathrm{DT} = P_e - \mathrm{LD} \tag{3}$$

The kinetic energy of the direct throughfall (*KE* (*DT*); J m^{-2}) is determined as a function of rainfall intensity (*I*; mm h^{-1}), using a typical value for the erosive rain of the climatic region. In Table 1 examples of equations for different regions with specific rainfall characteristics are given, which can be used to calculate *KE* (*DT*).

The kinetic energy of the leaf drainage (*KE* (*LD*); J m^{-2}) is a function of plant canopy height (*PH*; m) as proposed by Brandt (1990):

$$\mathrm{KE(LD)} = \left[\left(15.80PH^{0.5}\right) - 5.875\right]\mathrm{LD} \tag{5}$$

The total energy of the effective rainfall (*KE*; J m^{-2}) is the sum of the two energy components:

$$\mathrm{KE} = \mathrm{KE(DT)} + \mathrm{KE(LD)} \tag{6}$$

The annual surface runoff (*SR*; mm) is obtained from:

$$SR = Pexp\left(-\frac{S_c}{P_o}\right) \tag{7}$$

where P_o = the mean rain per rain day (mm) (i.e., mean annual rainfall *P* divided by the number of rainy days per year) and S_c = the soil moisture storage capacity (mm) and estimated as:

Table 1
Examples of equations for the calculation of rainfall kinetic energy (Morgan, 2001).

Kinetic energy equation[a]	Eq.	Suitability region	Reference
$KE(DT) = 11.87 + 8.73^{10} logI$	(4a)	North America, east of Rocky Mountains	Wischmeier and Smith (1978)
$KE(DT) = 8.95 + 8.44^{10} logI$	(4b)	Northwest Europe and similar climate zones	Brandt (1990)
$KE(DT) = 9.81 + 11.25^{10} logI$	(4c)	Regions with a Mediterranean climate	Zanchi and Torri (1980)
$KE(DT) = 35.9(1 - 0.56e^{-0.034I})$	(4d)	West Mediterranean	Coutinho and Tomás (1995)
$KE(DT) = 29.8 - (127.5/I)$	(4e)	Regions with tropical climates	Hudson (1965)
$KE(DT) = 9.81 + 10.60^{10} logI$	(4f)	East Asia	Onaga, Shirai, and Yoshinaga (1988)
$KE(DT) = 29.0(1 - 0.6e^{-0.04I})$	(4g)	Temperate southern hemisphere climates	Rosewell (1986)

[a] *KE (DT) = kinetic energy in J m^{-2} mm^{-1}; I = rainfall intensity in mm h^{-1}.*

$$S_c = 1000\ \text{MS BD EHD}\left(\frac{\text{Et}}{\text{Eo}}\right)^{0.5} \tag{8}$$

where *MS* = the gravimetric soil moisture content at field capacity (kg kg^{-1}), *BD* = the dry bulk density of the soil (Mg m^{-3}), *EHD* = the effective hydrological depth of the soil (m), and *Et/Eo* = the ratio of actual crop evapo-transpiration to maximum crop evapo-transpiration (mm mm^{-1}). The *EHD* indicates the depth of soil within which the moisture storage capacity controls generation of surface runoff. It is a function of plant cover, which influences the depth and density of roots, and, in some instances, the effective soil depth, for example on soils shallower than 0.1 m or where a surface seal or crust has formed (Morgan, 2001). There are some guide values of *EHD* for use with the rMMF model. Values range from 0.05 for bare and shallow soils on steep slopes, to 0.20 for forest soils (Morgan, 2005). The larger the *EHD*, the more water can be stored in the soil, and less surface runoff is produced. Typical values for *MS* and *BD* are provided by Morgan (2005). Generally, *BD* varies from 1.1 for a clay soil to 1.5 for a sand soil, and *MS* varies from 0.08 for a sand soil to 0.45 for a clay soil.

Soil particle detachment by raindrop (*F*; kg m^{-2}) is a function of total *KE* and soil erodibility:

$$F = 10^{-3} K\ \text{KE} \tag{9}$$

where *K* = soil detachability index (g J^{-1}), defined as the weight of soil detached from the soil mass per unit of rainfall energy. Soil particle detachment by surface runoff (*H*; kg m^{-2}) is estimated as:

$$H = 10^{-3}(0.5\text{COH})^{-1} SR^{1.5} \sin(S)(1 - \text{GC}) \tag{10}$$

where *COH* = cohesion of the soil surface (kPa), *S* = slope (°) and *GC* = fraction of vegetation ground cover (0–1). The equation assumes that soil particle detachment by surface runoff occurs only where the soil is not fully protected by ground cover. As a first approximation, this seems reasonable since a dense ground cover will dissipate most shear stress from surface runoff, leaving less shear stress for particle detachment. Values of *K* and *COH* for different soil textures are provided by Morgan (2005). *K* values vary from 0.05 for clay to 1.2 for sand, while values of *COH* vary from 2 for sand, loamy sand and sandy loam to 12 for clay.

The transport capacity is the maximum amount of sediment that a given volume of surface runoff can carry. The transport capacity of surface runoff (*TC*; kg m^{-2}) is calculated as:

$$\text{TC} = 10^{-3} C\ SR^2 \sin(S) \tag{11}$$

where *C* = crop or plant cover factor, which is an index (0.1–1) of soil loss at a given vegetation cover compared with the soil loss at bare soil. The *C* factor can be adjusted to take account of different tillage practices and levels of crop residue retention.

Eventually, the estimates of soil particle detachment by raindrop impact and by surface runoff are added together to give a total annual detachment rate. This is then compared with the annual transport capacity of the surface runoff and the lesser of the two values is the annual erosion rate *E* (kg m^{-2}):

$$E = \min[(F + H), \text{TC}] \tag{12}$$

2.2. Hillslope-scale rMMF model: the hMMF model

The field scale version of the rMMF model cannot be used to accurately calculate erosion on a natural hillslope with variations in slope steepness, soil properties, and vegetation cover. For such complex hillslopes, the hMMF model can calculate surface runoff volume and sediment transport using the following approach.

2.2.1. Hillslope properties

The hillslope is divided into $i = 1, \ldots, n$ sections of variable lengths and slope steepness. The first section starts at the top of the hillslope, and section *n* is the lowest section of the slope. A similar approach was used by Morgan and Duzant (2008), but their approach results in different and sometimes unrealistic surface runoff amounts (see Appendix A). Each section has its own soil and vegetation characteristics, but it is assumed that the amount of annual rainfall is homogeneous over the entire hillslope. In this way, complicated slope profiles can be simulated.

2.2.2. Surface runoff

The surface runoff along the slope is calculated by summing the volume of surface runoff generated in a particular section with the surface runoff coming from the immediate upslope section. The annual surface runoff of the first (top) section is calculated according to eq. (7). This amount in mm is converted to a volume per meter width by multiplying SR_1 with the length of the slope section (L_1):

$$SR'_1 = 10^{-3} SR_1 L_1 \tag{13}$$

where SR'_1 is in m^2. For the second section, the total volume of surface runoff is equal to the volume that is generated by the section itself plus the volume that is flowing in from the upper section:

$$SR'_2 = 10^{-3} SR_2 L_2 + SR'_1 \tag{14}$$

where SR'_2 is again in m^2. For a hillslope consisting of $i = 1, \ldots, n$ sections, eq. (14) can be generalized to:

$$SR'_i = 10^{-3} SR_i L_i + SR'_{i-1} \tag{15}$$

The SR'_0 is the boundary condition and equal to zero, meaning that there is no inflow coming from above.

2.2.3. Surface runoff infiltration

In the original, field-scale rMMF version it is assumed that all surface runoff will flow down the field, and there is no infiltration of surface runoff possible. For natural hillslopes this is unrealistic as infiltration of surface runoff may occur. However, simulating infiltration of surface runoff in a (semi-)empirical model is difficult, as there is no physically-based infiltration sub-model and generally few data are available on surface runoff infiltration along hillslopes. In the hMMF version it simply has been solved by introducing a new variable, SR_i^{inf}, which accounts for the fraction (0–1) of surface runoff infiltrating in a particular section. The new surface runoff calculation that accounts for surface runoff infiltration becomes then:

$$SR_i'' = (SR_i' + SR_{i-1}'')\left(1 - SR_i^{inf}\right) \quad (16)$$

2.2.4. Sediment transport

The actual sediment transport along the hillslope depends on the calculated amounts of detachment and the transport capacity of the surface runoff. In the rMMF model, the amount of surface runoff in mm (SR) was used in eq. (10) and eq. (11). But, in the case of a continuous hillslope, the amount of surface runoff in mm can be already very high at the first section, while the actual volume of surface runoff is low. This may lead to unrealistic values for H and TC. Therefore, in the new calculations of detachment by surface runoff and transport capacity, the SR_i'' values (in m^2) are used for each slope section. Two new equations have been developed based on literature (Aksoy & Kavvas, 2005; Julien & Simons, 1985; Prosser & Rustomji, 2000; Zhang et al., 2011), while retaining the simplicity of eq. (10) and eq. (11). The annual detachment by overland flow is calculated by:

$$H_i' = (0.5COH_i)^{-1}(SR_i'')^{2.5}S_i'(1 - GC_i) \quad (17)$$

where S_i' is slope gradient ($m\ m^{-1}$). The annual transport capacity equation becomes:

$$TC_i' = C_i(SR_i'')^{\beta}S_i' \quad (18)$$

where TC_i' is now in $kg\ m^{-1}$. The coefficient β is a variable that can be used to calibrate the soil erosion in case quantitative data are available. If no data is available, a value of 1.5 is recommended (Prosser & Rustomji, 2000).

The actual amount of sediment transport in a certain section (ST in $kg\ m^{-1}$) is dependent on the amount that is generated by that section (the total detachment) and the amount of sediment already in transport. First the sediment transport deficit (ST_i^{def} in $kg\ m^{-1}$) for section i is calculated by withdrawing the incoming sediment transport from above from the transport capacity of the section:

$$ST_i^{def} = TC_i' - ST_{i-1} \quad (19)$$

ST_0 is the boundary condition and equal to zero, meaning that no sediment is entering from above. Depending on the value of ST_i^{def} the following rules apply:

- If $ST_i^{def} < 0 \rightarrow ST_i = TC_i'$ (deposition in section)
- If $ST_i^{def} = 0 \rightarrow ST_i = TC_i'$ (transport only; no soil loss or deposition)
- If $ST_i^{def} > 0$ then ST_i depends on the total detachment of the section:
  - o If $(F_i + H_i')L_i \geq TC_i' \rightarrow ST_i = TC_i'$ (detachment exceeds transport capacity)
  - o If $(F_i + H_i')L_i < TC_i' \rightarrow ST_i = ST_{i-1} + (F_i + H_i')L_i$ (transport capacity exceeds detachment)

3. hMMF model application

The hMMF model was tested using several datasets. First, the hMMF was compared with the rMMF model using the same surface runoff and erosion data as used by Morgan (2001) to test the rMMF. Those data were derived from a large number of published studies from different countries and described by Morgan and Finney (1982). The results of the model comparison are provided in Appendix B. Further hMMF model testing was done by using original USLE plot data, an experimental hillslope in Hungary, a surveyed hillslope in NW Tunisia, and some hypothetical hillslope situations to show its potential for simulation of surface runoff, sediment transport and the impacts of SWC measures on surface hydrology and erosion. The first application is using data from USLE plots at Beemerville, New Jersey, USA. The second application is based on the experimental plot data of Hudek and Rey (2009), which were also used by Hudek et al. (2014) to run the field scale rMMF erosion model. The third application is the modelling of a long (1711 m) hillslope from NW Tunisia on which an erosion survey was conducted by Sterk (2009). Hypothetical hillslope runs were based on the same hillslope of Hudek and Rey (2009). Two different aspects were tested: 1. The effect of infiltration of surface runoff on sediment transport; 2. The possibility of simulation of SWC measure impacts on surface runoff and sediment transport.

3.1. hMMF testing using beemerville USLE erosion data

The United States Department of Agriculture (USDA) has made available some of the original data that were measured on erosion plots (https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosion-research/docs/usle-database/usle-data/), and used for the development of the USLE. Here the available data of rainfall, surface runoff, soil loss, and crop management from the six plots at Beemerville were used to test the hMMF model. This dataset comprises the years 1938–1940, which have complete records. All plots were 21.4 × 4.3 m in size, the slope was 9.4°, and the soil texture type was loam. Three cropping systems were used:

- Maize crop planted up/down (plots 1 & 3)
- Maize planted along contour (plots 2 & 4)
- Mixed grass and legumes (plots 5 & 6)

The rainfall, surface runoff and soil loss data were averaged for the three years of measurement, and for the three cropping systems (Table 2). Then the hMMF was first run using recommended variable values (Morgan, 2005, Table 3). The results of the hMMF calculations are in Table 2 and show that the model consistently underestimates the amount of surface runoff by 6 mm (plots 5 & 6), by 17 mm (plots 2 & 4) to 26 mm (plots 1 & 3). The modelled values of soil loss are reasonably good in two cases (plots 2 & 4; plots 5 & 6), but for plot 1 & 2 the soil loss is 83.2% lower than the measured value. This is due to the relatively small amount of surface runoff which leads to a relatively low annual transport capacity. The underestimation of surface runoff by using recommended input variable values is similar to the results of the rMMF and hMMF comparison in Appendix B. In general, the recommended values of

Table 2
Characteristics and average measured rain, surface runoff and erosion values of the Beemerville erosion plots during the years 1938–1940.

Plots	Land use	Rain	Rain days	Surface runoff		Soil loss	
				measured	modelled	measured	modelled
		mm	no.	mm	mm	$kg\ m^{-2}$	$kg\ m^{-2}$
1 & 3	Maize (up-down)	1177	111	131	105	1.73	0.29
2 & 4	Maize (contour)	1177	111	103	86	0.29	0.22
5 & 6	Grass + herbs	1177	111	61	55	0.01	0.11

Table 3
Recommended variable values used for the hMMF modelling of the Beemerville erosion plots for the years 1938–1940.

Plots	*A*	*CC*	*I*	*PH*	*MS*	*BD*	*EHD*	*Et/Eo*	*K*	*COH*	*GC*	*C*	*β*
	–	–	$mm\ h^{-1}$	m	wt.%	$Mg\ m^{-3}$	m	–	$g\ J^{-1}$	kPa	–	–	–
1&3	0.15	0.45	10	0.82	0.2	1.3	0.12	0.68	0.80	3	0.10	0.20	1.5
2&4	0.15	0.45	10	0.82	0.2	1.3	0.13	0.68	0.80	3	0.10	0.20	1.5
5&6	0.30	0.90	10	0.10	0.2	1.3	0.14	0.80	0.80	3	0.80	0.20	1.5

EHD (Morgan, 2005) result in an underestimation of the surface runoff amounts.

It is fairly easy to match the hMMF values of surface runoff by changing the *EHD* variable, while the β variable can be changed to modify the sediment transport capacity and thus the soil loss. By changing the *EHD* into 0.109 and the β into 2.88 gives the exact same surface runoff and soil loss values as measured on plots 1 & 3. For plots 2 & 4 changing *EHD* into 0.121 and β into 1.51 gives exact matches with the measured values, and for plots 5 & 6 this is achieved by changing *EHD* into 0.135 and β into 1.00.

3.2. hMMF application at 30-m hillslope in Hungary

Hudek and Rey (2009) measured surface runoff and soil loss from erosion plots at Szentendre in the north of Hungary. All plots were 30 m long and had a linear slope of 8°. The plots had different treatments. One plot was bare (=control), while the other plots had a cover of *M. aquifolium* shrubs of different ages (4, 12, 20, 25 years). Here only the data from the bare plot and the 4-year old *M. aquifolium* plot were used. Erosion measurements were conducted for one full year (June 2007–May 2008). Details about the plots and the measured amounts of surface runoff and soil loss are in Table 4. The same variable values as used by Hudek et al. (2014) for the field scale rMMF application were used here for the hMMF model (Table 5). Eq. (4b) was used for the calculation of the rainfall kinetic energy. The hillslope was represented in the model by ten equal sections of 3 m each.

Fig. 1 shows the hMMF results of annual surface runoff and sediment transport along the 30 m slope for bare soil (Fig. 1a) and the 4-year *M. aquifolium* cover (Fig. 1b). The surface runoff shows a linear increase because the soil and vegetation variables are kept constant along the slope, and no surface runoff infiltration was allowed ($SR_i^{inf} = 0$). The sediment transport profile shows a realistic pattern. It is near zero at the top of the slope and remains small till approximately 6 m on the bare plot, and about 15 m on the *M. aquifolium* plot. From those points downward the sediment transport rapidly increases due to the increase in transport capacity of the surface runoff. The sediment transport on the bare soil is transport capacity limited up to 12 m and from there on becomes detachment limited to the end of the slope. For the *M. Aquifolium* plot, sediment transport is limited by the transport capacity on the upper part of the slope, but changes to detachment limited transport from 18 m to the end of the slope.

For the bare soil (Fig. 1a) the modelled annual surface runoff from the slope is 383.5 mm and the corresponding soil loss equal to 2.21 kg m^{-2}, which exactly matches the measured amounts of Hudek and Rey (2009). For the situation with vegetation cover, the modelled surface runoff is 116.7 mm and the soil loss equal to 0.56 kg m^{-2}. Again, these results match closely the observed surface runoff and soil loss values of Hudek and Rey (2009) (Table 4). The close match between measured and modelled surface runoff is because of the calibrated *EHD* values by Hudek et al. (2014). To obtain the correct soil losses with the hMMF version, the value β in eq. (18) was calibrated at 2.52 for the bare soil and 4.85 for the plot with *M. aquifolium* cover. When the recommended values for *EHD* (0.05 for control; 0.10 for *M. aquifolium*) are used the calculated surface runoff is 5.7% (control) and 40.7% (*M. aquifolium*) lower than the measured values. Using the recommended value for β (= 1.5) for both plots, the calculated soil loss is 92.3% lower in the control plot and no erosion is calculated in the *M. aquifolium* plot. This example shows the need for soil erosion measurements to allow model calibration, as in this case the recommended values result in a strong underestimation of the measured erosion values.

3.3. hMMF application at a 1711-m hillslope in Tunisia

Sterk (2009) conducted an erosion survey at the Barbara watershed in Tunisia as part of a WorldBank project on sustainable land use. Actual measurements of surface runoff and sediment transport were not available. Instead, detailed erosion descriptions were made along two hillslopes draining into the Barbara river. One

Table 4
Characteristics and measured surface runoff and soil losses of two erosion plots at Szentendre, Hungary (Hudek & Rey, 2009).

Plot	Soil texture	Length	Slope	Slope type	Rain	Rain days	Surface runoff	Soil loss
		m	°		mm	no.	mm	$kg\ m^{-2}$
Bare	Clay loam	30	8	Linear	551.5	86	383.0	2.20
M. aquif.	Clay loam	30	8	Linear	551.5	86	118.2	0.56

Table 5
Variable values used for the hMMF modelling of two erosion plots at Szentendre, Hungary (Hudek et al., 2014). No surface runoff infiltration was allowed ($SR_i^{inf} = 0$).

Plot	*A*	*CC*	*I*	*PH*	*MS*	*BD*	*EHD*	*Et/Eo*	*K*	*COH*	*GC*	*C*
	–	–	mm h^{-1}	m	wt.%	Mg m^{-3}	m	–	g J^{-1}	kPa	–	–
Bare	0	0	10	0	0.24	1.01	0.043	0.05	0.25	10	0	1.00
M. aquif.	0.11	0.31	10	0.22	0.24	1.01	0.075	0.30	0.25	10	0.42	0.30

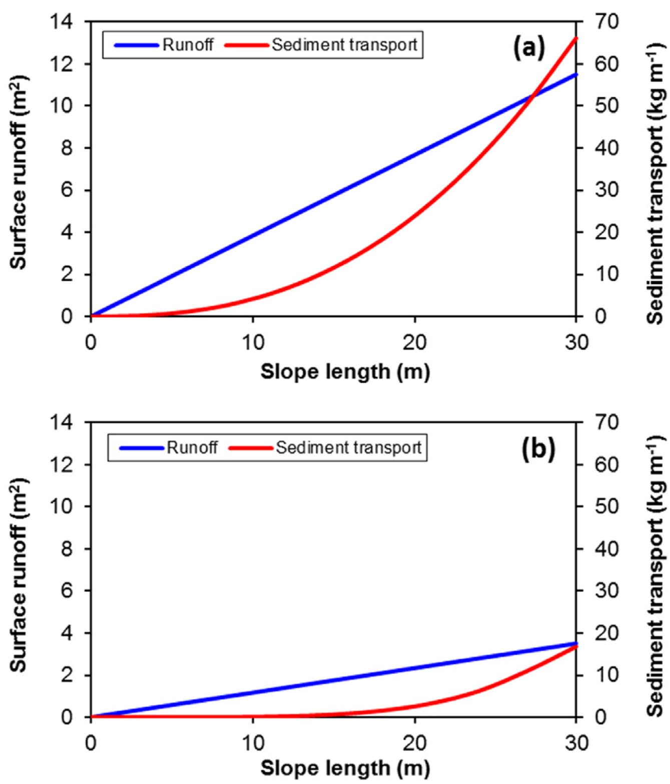

Fig. 1. Surface runoff and sediment transport modelled with the hMMF hillslope erosion model along a 30 m linear slope at Szentendre, Hungary. (a) for bare soil conditions; (b) for a 4 year *M. aquifolium* vegetation cover.

of these transects was used here to illustrate the possibility of simulating erosion and deposition along an irregular hillslope with the hMMF model.

The Barbara watershed is located in Northwest Tunisia, near to the town Aïn Draham. The dam of the Barbara reservoir is at 36° 44′ 2.28″ N; 8° 31′ 54.30″ E, and the watershed stretches in South-western direction from there. A small part of the watershed (17 km^2) is located in Northeast Algeria. The size of the watershed upstream of the dam is 177 km^2. Altitude in the watershed ranges from 180 to 1200 m. Climate in the region is of the Mediterranean type, with dry summers and wet winters. The average annual rainfall is approximately 800 mm, with frequently high intensity rainstorms.

The Barbara watershed is composed of a complex topography with slopes varying from flat to very steep (>25°). Soils have textures varying from sandy loam to clay, with moderate rock content, and a generally good soil structure. Land use in the watershed consists mainly of cropland (39.2%), grassland (3.0%), forest (24.9%), agroforestry (13.9), scrubland (4.0%) and natural vegetation (8.2%). The entire watershed was under a low to moderate vegetation cover varying between 10% and 50%. The major crops in the watershed are olives, cereals and beans (Sterk, 2009).

The transect used for the modelling has a length of 1711 m and runs from SSE towards the NNW. It drains into a tributary of the Barbara river. The elevation of this transect goes from 442 m to 198 m. Land use varies from a natural vegetation or grass cover on the highest part to arable cropland in the middle part, and arable cropland combined with acacia tree agroforestry in the lower part of the hillslope. The transect was divided into 18 sections of approximately 95 m length for which the average slope, soil type (texture), the land use, and erosion severity was determined. The transect starts with a steep slope on the upper part, decreasing towards the middle, but then increasing again until an almost flat part in the lower middle part of the hillslope. From there the slope angle increases, but before reaching the Barbara river it decreases again.

The hMMF modelling was based on the same 18 slope sections measured in the survey. The main model variables, except slope degree, were grouped into three categories based on the land use along the hillslope (Table 6). The annual amount of rainfall and number of rain days used was based on the measured data at the Barbara dam and equal to 812 mm and 62 days. Eq. (4c) was used to calculate the rainfall kinetic energy. The hMMF variable values per slope category are provided in Table 7. No surface runoff infiltration was allowed ($SR_i^{inf} = 0$).

The hMMF model calculated 145 mm of surface runoff and a soil loss of 0.22 kg m^{-2} for the entire slope. The modelled sediment transport and related mass balance values were plotted along the hillslope profile using SURFER 8.05 (Golden Software). Sediment transport is low at the upper part of the hillslope (Fig. 2a) due to the good vegetation cover. Here the erosion process is transport capacity limited. In the middle part the amount of surface runoff strongly increases (not shown here) but the erosion process remains transport capacity limited all the way down to the end of the slope. In the middle part, first the slope steepness increases and the sediment transport increases strongly, leading to a negative mass balance (Fig. 2b; between 1200 and 1000 m). Below this zone, the slope angle decreases again, resulting in a lower sediment transport. Much of the eroded sediment is deposited in this section (Fig. 2b; between 1000 and 850 m). The same pattern is repeated further downslope, with a strong increase in erosion and sediment transport between 400 and 200 m. Again below the steep zone there is much deposition (Fig. 2b; between 200 and 30 m) due to the smaller slope angle and the actual soil loss from the entire slope is low. Fig. 3 shows an example of actual sediment deposition on a part of the hillslope (at ~900 m) with a small slope angle.

3.4. hMMF application at 30-m hillslope in Hungary: surface runoff infiltration

For this application the 30-m bare soil slope of Hudek and Rey (2009) was used. The simulation of surface runoff and sediment transport along the hillslope with and without any surface runoff infiltration is provided in Appendix C. The inclusion of surface runoff infiltration was achieved by modifying the SR_i^{inf} value along the slope. The results (Figure C1) show that the surface runoff

Table 6
Characteristics a hillslope transect in the Barbara watershed, Tunisia (Sterk, 2009).

Part	Length	Slope	Slope type	Soil texture	Land use	Erosion severity
	M	°				
Upper	678	11.6	Concave	Loam	Natural vegetation/grass	Negligible
Middle	563	5.9	Concave	Loam	Crop land	Moderate rill erosion
Lower	470	5.5	S-shape	Sandy loam	Crop land/agro-forestry	Severe rill erosion

Table 7
Variable values used for the hMMF modelling of a hillslope in the Barbara watershed, Tunisia (Sterk, 2009). No surface runoff infiltration was allowed ($SR_i^{inf} = 0$).

Part	*A*	*CC*	*I*	*PH*	*MS*	*BD*	*EHD*	*Et/Eo*	*K*	*COH*	*GC*	*C*	*β*
	–	–	mm h^{-1}	m	wt.%	Mg m^{-3}	m	–	g J^{-1}	kPa	–	–	–
Upper	0.10	0.2	30	0.2	0.28	1.2	0.08	0.8	0.7	2	0.20	0.01	1.90
Middle	0.10	0.3	30	0.5	0.20	1.3	0.10	0.6	0.8	3	0.25	0.20	1.90
Lower	0.15	0.4	30	1.0	0.20	1.3	0.11	0.7	0.8	3	0.30	0.15	1.90

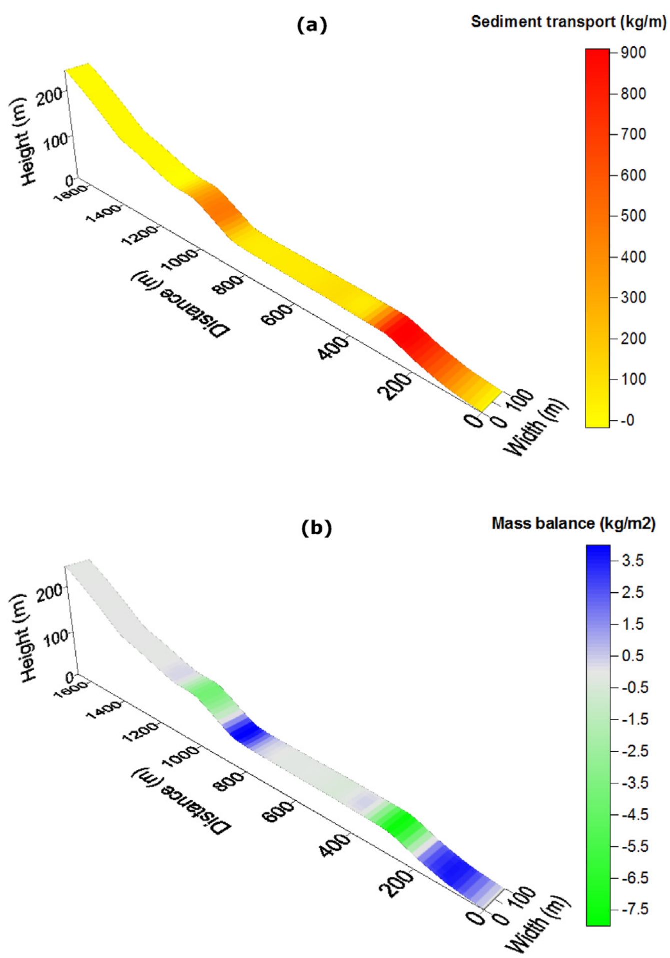

Fig. 2. Erosion modelled with the hMMF model along a hillslope in the Barabara watershed, NW Tunisia. (a) sediment transport profile along the slope; (b) mass balance profile showing erosion (green) and deposition (blue) zones.

profiles become curved and result in less surface runoff from the slope. The obtained profiles (Figures C1c-d) are realistic for natural hillslopes (Sheridan et al., 2014), but it remains uncertain what appropriate values of the SR_i^{inf} variable are, as data of surface runoff infiltration along hillslopes are scarce, if available at all. The lower surface runoff amounts obviously lead to lower sediment transport and soil losses (Figure C1).

3.5. hMMF application at 30-m hillslope in Hungary: SWC measures

The advantage of the hillslope version of the hMMF model is that it can directly incorporate SWC measures such as grass strips and bench terraces. Such structures stimulate surface runoff infiltration at the grass strip or on the near level bench terrace surface, which can be simulated through the SR_i^{inf} variable.

Fig. 4 shows simulations of grass strips on the 30-m bare soil plot at Szentendre, Hungary (Hudek & Rey, 2009). Fig. 4a and b shows respectively the impacts of a single, 1-m wide grass strip at the middle and at the end of the plot. The surface runoff infiltration was set at 25% ($SR_i^{inf} = 0.25$) for the grass strip. This reduces surface runoff from the slope with the grass strip in the middle from 383 mm to 327 mm, compared to the situation without a grass strip (Fig. 1a). Erosion is subsequently reduced by 0.73 kg m^{-2} (from 2.21 to 1.48 kg m^{-2}), mainly due to the deposition of eroded sediment at the grass strip. A grass strip at the end of the plot (Fig. 4b) results in even more reduction. Surface runoff is reduced to 282 mm and soil loss to 0.51 kg m^{-2}. These results nicely show the effects of a grass strip at the end of a slope: part of the surface runoff is passing through, but the bulk of sediments is filtered from the running water and deposited in the strip. Such grass strips are often termed Vegetative Filter Strips (e.g. Abu-Zreig et al., 2004). The third simulation (Fig. 4c) shows the effects of two grass strips, one in the middle and one at the end. In this case only 243 mm of surface runoff passes the lower strip and the hillslope soil loss is reduced to 0.35 kg m^{-2}.

The last example (Fig. 5) shows the simulation of three bench terraces of 10 m wide (Fig. 5a). An infiltration of surface runoff at the bench surface of 50% ($SR_i^{inf} = 0.5$) was assumed. The resulting surface runoff and soil loss are 68 mm and 0.29 kg m^{-2}. The hMMF model only calculates erosion along the risers of the terraces, and this sediment is deposited on the next bench terrace surface (Fig. 5b). Hence, the calculated soil loss for the entire field actually comes only from the lowest riser, which is consisting of bare soil in the calculation. If a grass cover on the risers is simulated, the surface runoff becomes 49 mm and the soil loss 0.09 kg m^{-2}.

4. Discussion

The comparison between the original rMMF and the hMMF simulation results (Appendix B) shows that the rMMF performed better than the hMMF when using recommended values for *EHD*

Fig. 3. Sediment deposition at a nearly flat area along a hillslope in the Barabara watershed, NW Tunisia.

and β. In general, the *EHD* values recommended by Morgan (2005) resulted in an underestimation of the amounts of measured surface runoff. This underestimation subsequently led to an underestimation in the soil loss values. By calibrating the variables *EHD* and β, the hMMF simulations exactly matched the measured surface runoff amounts, while the simulated soil losses were close to the measured values.

The applications of the hMMF model in the US, Hungary and Tunisia show that the model is capable of reproducing measured surface runoff and erosion rates from the erosion plots in Beemerville (Table 2) and Szentendre (Fig. 1), as well as erosion/deposition patterns along the hillslope in the Barbara watershed (Fig. 2). For the Beemerville plots the hMMF simulated surface runoff underestimated the measured values by 9.1%–19.8% when the recommended model variable values were used. For the Hungarian plots the underestimation of surface runoff was 5.7% for the bare plot and 40.7% for the *M. aquifolium* plot using recommended values. Except for the latter value, the overall performance for surface runoff can be considered reasonably good. Given the general underestimation of surface runoff when using recommended *EHD* values there is a need to re-analyse the *EHD* values for a wide range of soil erosion studies to improve the recommended values for different bio-physical conditions.

For soil losses the hMMF modelled values were very different from the measured values. Only on plots 2 & 4 at Beemerville a relatively low underestimation of 24.1% was obtained; all other simulation resulted in differences of 83.2% or more. However, by changing the *EHD* and β values, the model could be calibrated in such a way that the measured and modelled values of surface runoff and soil loss exactly match. It is however questionable if this exact match between measured and modelled values is really needed in most model studies. It is well known that most, if not all, plot-based erosion measurements are inherently variable, both in spatial and temporal sense (Nearing & Hairsine, 2016; Wendt et al., 1986). The uncertainty in the measured values of surface runoff and soil loss may subsequently lead to modelling efforts that try to reproduce a situation that is inherently variable. In addition, uncertainty in model equations as well as model input variable values further complicate the accuracy of the modelling process (Beven & Brazier, 2016). Hence, reproducing spatial patterns of erosion, like in the case illustrated in Figs. 2 and 3, could sometimes be more relevant than trying to reproduce actual measured erosion values.

In the hMMF model version two new variables are introduced: SR_i^{inf} and β. The SR_i^{inf} variable in eq. (16) accounts for infiltration of upslope generated surface runoff, and is especially useful for simulating the effects of SWC measures on soil erosion (Figs. 4 and 5). As shown in Appendix C, SR_i^{inf} can be used also to model infiltration along a hillslope without SWC measures, which naturally occurs in downslope areas (Langhans et al., 2014). The resulting profiles (Figs. C1c & C1d) compare well with experimentally determined profiles (Sheridan et al., 2014), but obtaining correct values for SR_i^{inf} along a certain hillslope remains challenging. This would require detailed measurements of surface runoff depths and infiltration amounts at different sections on a hillslope.

The value of β which has been introduced in the modified transport capacity equation (eq. (18)) actually regulates the annual sediment transport rate. In many cases the erosion process in the hMMF is transport capacity limited, so by increasing β to a higher value, the amount of sediment transport is enhanced. Likewise, a lower value of β decreases the sediment transport along the hillslope. Currently one single value of β is used for each section of the hillslope, but it would be possible to have separate values of β for each hillslope segment. However, obtaining the actual values of β along a complex hillslope is complicated as observations of sediment transport along a hillslope profile usually are unavailable. In case no sediment transport data from the hillslope are available, a value of 1.5 is recommended, which is based on the review of sediment transport capacity studies by Prosser and Rustomji (2000).

The hMMF model has an annual time step, which can be considered appropriate for the modelling of SWC measures. By

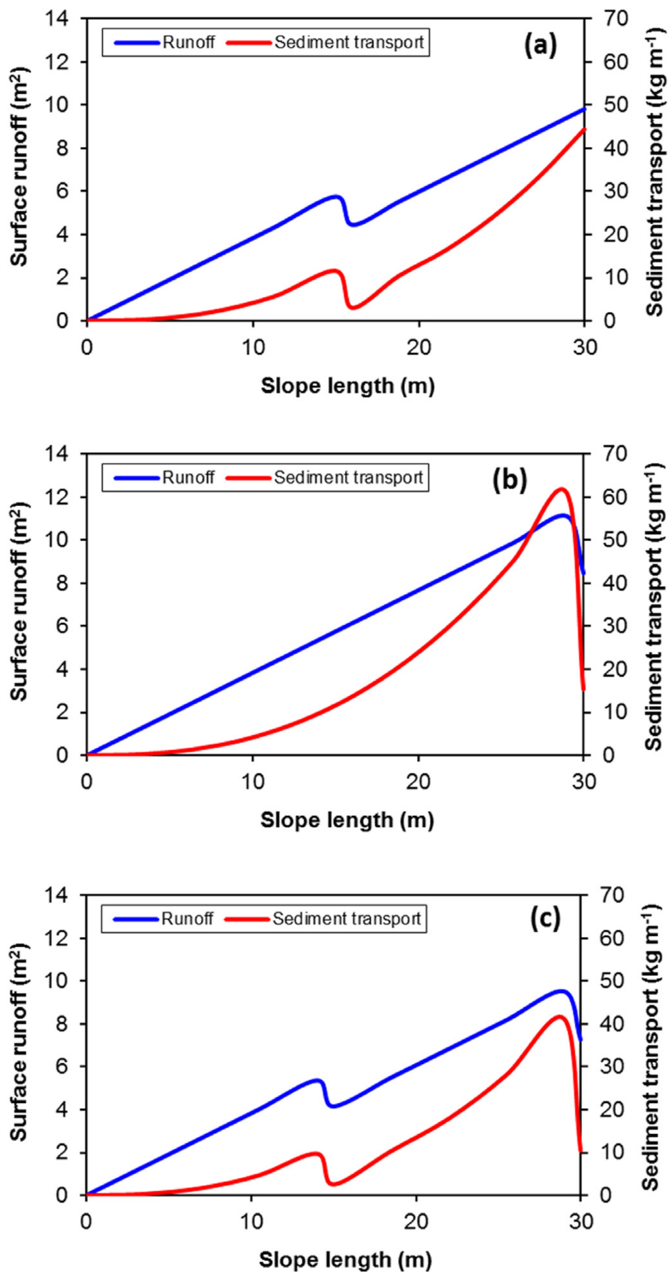

Fig. 4. The influence of grass strips on surface runoff and sediment transport along a 30-m hillslope at Szentendre, Hungary. (a) simulation of a 1-m wide grass strip at the middle of the plot; (b) simulation of a 1-m wide grass strip at the end of the plot; (c) simulation of two 1-m wide grass strips at the middle and end of the plot. In the simulations, a surface runoff infiltration of 25% ($SR_i^{inf} = 0.25$) was assumed, and no surface runoff infiltration in the rest of the plot.

incorporating the SWC structures in the hMMF model the impacts they have on surface runoff and sediment transport can be simulated (Figs. 4 and 5). It is unlikely that a shorter time step (event, daily, monthly) would show different impacts of SWC structures. The only reason to have an event-based simulation could be that the effects of extreme events could be better captured, and actually may show a different response as compared to the annual based simulations. But, changing the model from its current annual time step to a daily or event time step is not trivial, and will require new equations and new model variables (e.g. Shrestha & Jetten, 2018).

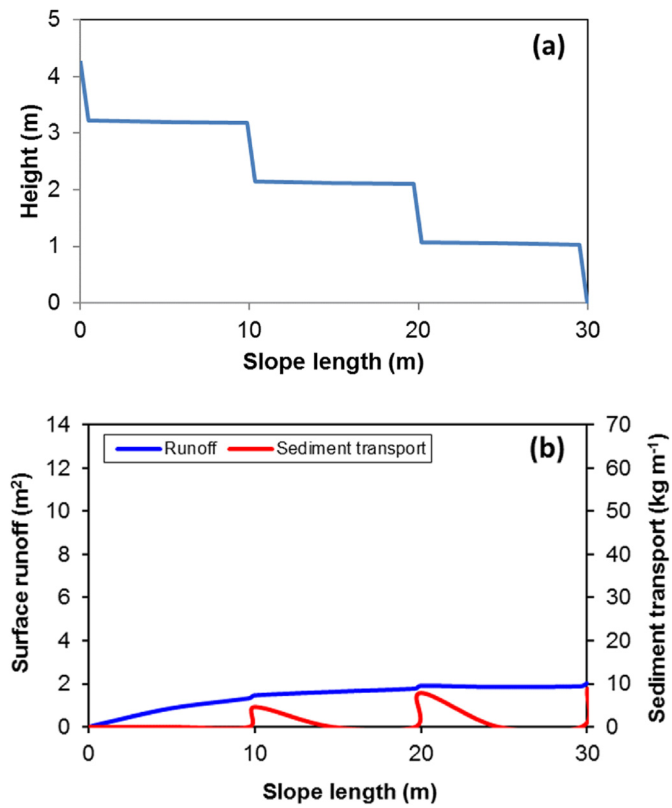

Fig. 5. hMMF simulation of bench terraces on a 30-m hillslope at Szentendre, Hungary. (a) The slope profile showing the terraces; (b) the simulated surface runoff and sediment transport along the bare slope. In the simulations of bench terraces a 50% ($SR_i^{inf} = 0.50$) surface runoff infiltration on the bench surface was assumed, and no surface runoff infiltration on the bare risers.

Another problem with the simulations of SWC structures is the lack of knowledge about the amount of infiltration of surface runoff generated by the specific measures. For instance, the amount of surface runoff infiltration on the bed of a bench terrace can be assumed to be high, but not much information on this can be found in the SWC literature. The same holds for grass strips and how much surface runoff infiltration and sediment filtering those strips may cause. A few studies exist where the amounts of surface runoff infiltration and sediment trapping were measured in grass strips (e.g. Van Dijk et al., 1996) and by bench terraces (e.g. Tenge et al., 2011). The hMMF modelled reductions in soil losses varied from 33.0% for the case with a grass strip in the middle of the field (Fig. 4a), to 76.9% for the grass strip at the end of the field (Figs. 4b), and 84.2% for the case with two grass strips (Fig. 4c). The latter two reductions are in the same range as reported soil erosion reductions by grass strips in Van Dijk et al. (1996). Measured soil losses on fields with bench terraces in the West Usambara Mountains ranged from 0.15 to 0.37 kg m^{-2} (Tenge et al., 2011), which is similar to the amount modelled with hMMF in Fig. 5 (0.29 kg m^{-2}). Hence, the hMMF simulations of SWC measures led to similar reductions in erosion as reported in a few studies.

5. Conclusions

The semi-empirical rMMF soil erosion model is a relatively easy to apply, but good model for field-scale water erosion quantification. Two shortcomings of the rMMF are 1. The assumption of a homogeneous and linear slope of the field, and 2. The incorporation of SWC measures through the USLE *P*-factor only. The new hMMF version is capable to simulate surface runoff and sediment transport along irregular hillslope profiles with or without SWC measures. By introducing a surface runoff infiltration factor (SR_i^{inf}) in the model equations the effects of SWC measures can be directly simulated, and the effectiveness of different measures can be quantified. Therefore, the hMMF allows designing appropriate SWC measures for specific hillslope conditions.

The model was tested against one hillslope erosion survey and quantitative datasets of surface runoff and soil loss values from experimental plots. The overall performance of hMMF simulation of surface runoff ranged from poor to reasonably good. The evaluation resulted in a general tendency of underestimation of measured amounts when the recommended model variable values were used. It is concluded that the *EHD* values recommended by Morgan (2005) are generally too large and result often in an underestimation of the surface runoff amounts. It is therefore needed to re-analyse those recommended *EHD* values and improve them for a wide range of bio-physical conditions. Simulation of soil losses using recommended values resulted in large errors. Hence calibration of model variable values is generally needed to obtain a good match between modelled and measured soil loss values. The examples from Beemerville, USA, and Szentendre, Hungary, show that with calibration of the model variables *EHD* and β it is possible to get nearly exact matches between measured and modelled values.

The modelling of grass strips (Fig. 4) and bench terraces (Fig. 5) shows the capability of the hMMF model to quantify the impacts of such SWC structures on surface runoff and soil erosion. The simulated patterns of surface runoff and sediment transport are realistic, but actual data on the amounts of surface runoff infiltration and sediment filtering are scarce. Comparisons with reported experimental values are in the same range as modelled in this study. Hence it can be concluded that the hMMF model is able to simulate SWC structures directly instead of using the USLE *P* factor, as it mostly done. Therefore, the hMMF provides a tool for design and testing of SWC conservation measures under variable bio-physical conditions, such as slope angle, soil type, rainfall characteristics, and vegetation cover.

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Declaration of competing interest

I herewith confirm that there is no conflict of interest whatsoever with the contents of the manuscript “A hillslope version of the revised Morgan, Morgan and Finney water erosion model”.

Appendix A

Comparison between the Morgan/Duzant rMMF and hMMF models

Morgan and Duzant (2008) modified the rMMF model by adding new equations and changing some of the existing equations to better quantify effects of vegetation on water erosion. One of the changes was a modification of the surface runoff equation (eq. (7)) to make it applicable for slope lengths longer than 10 m that are divided in sections:

$$SR = (P + SR_{up})\exp\left(-\frac{S_c}{P_o}\right)\left(\frac{L}{10}\right)^{0.1} \quad \text{A.1}$$

where SR_{up} (mm) is the surface runoff coming from the upper section and *L* is the slope length (m). The last term on the right-hand side of eq. (A.1) is an empirical adjustment for slope length to correct for the sensitivity of the equation for the number of elements at which a long slope of maximum 50 m is divided.

A simple rMMF model was created for a 50 m linear slope, divided in five sections of 10 m each. Eq. (A.1) was used for the surface runoff calculation, and the results are compared here with the hMMF procedure for the same slope and model variables. The simulation is for a bare soil. The input values for both models are shown in Table A1. For the calculation of the kinetic energy of the direct throughfall (*KE* (*DT*)) eq. (4b) (Table 1) was used.

Table A.1
Input variable values used in hMMF and the rMMF modified model version of Morgan and Duzant (2008) for the simulation of a 50 m linear hillslope with a 5° slope angle and bare soil.

Variable	Value	Variable	Value
Rain (*P*)	600 mm	Bulk density (*BD*)	1.3 Mg m^{-3}
Rain days (P_o)	80 days	Effective hydraulic depth (*EHD*)	0.06 m
Interception (*A*)	0	Evapo-transpiration ratio (E_t/E_o)	0.05
Canopy cover (*CC*)	0	Soil particle detachment (*K*)	0.7 g J^{-1}
Plant height (*PH*)	0 m	Cohesion (*COH*)	10 kPa
Rainfall intensity (*I*)	10 mm h^{-1}	Ground cover (*GC*)	0
Soil moisture content (*MS*)	0.40 kg kg^{-1}	Crop cover factor (*C*)	1

The resulting patterns of hillslope surface runoff and sediment transport are shown in Figure A1. The hMMF calculates an annual surface runoff equal to 237 mm and a soil loss of 0.84 kg m^{-2}. The surface runoff increases linearly with slope length, while the sediment transport starts low at the upper slope and increases rapidly on the lower part of the slope, after approximately 25 m (Figure A1a).

The Morgan/Duzant rMMF model, using Eq. (A.1) for the surface runoff calculation, results in 507 mm of surface runoff and a soil loss of 7.35 kg m^{-2}. This is highly unrealistic, which can be easily seen from the slope profiles of surface runoff and sediment transport (Figure A1b). The high volume at the uppermost section immediately leads to unrealistically high sediment transport values. The problem with eq. (A.1) is that it sums the surface runoff values in mm, while these should first be converted to a volume before summing them. Then the sediment transport calculation would also become more realistic.

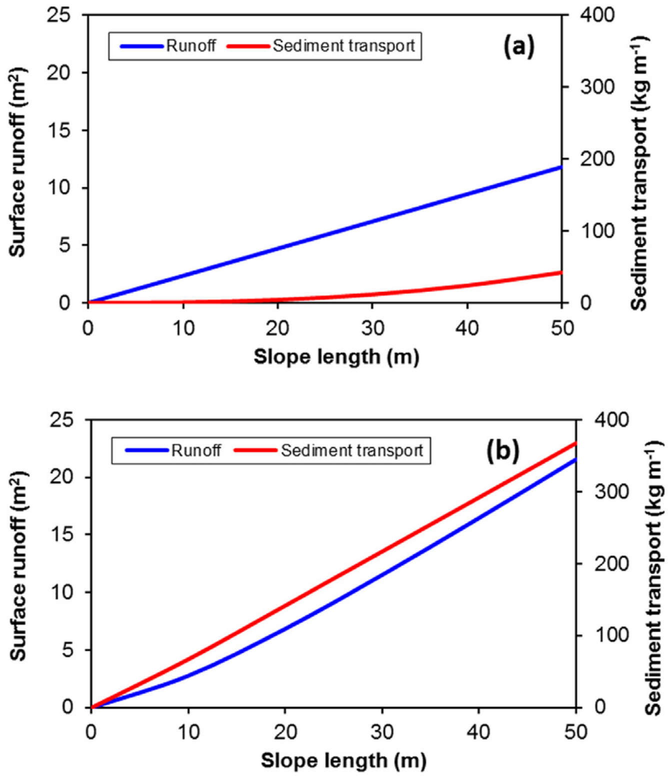

Fig. A.1. Simulated profiles of surface runoff and sediment transport with the hMMF model (a), and the rMMF model as modified by Morgan and Duzant (2008) (b).

Appendix B

Comparison of the hMMF with the rMMF model using measured soil erosion data

The hMMF and rMMF models were compared by simulating surface runoff and soil loss values from nine different locations. The data used were collected and described by Morgan and Finney (1982) to test the initial MMF model. Morgan (2001) used the same data to test the rMMF model, and here the same observations were used to calculate surface runoff and soil losses with the hMMF (Table B1). Not all data as used by Morgan (2001) could be used here, as for several sites details about soil type, crop type, slope steepness and rainfall were not provided by Morgan and Finney (1982). Another problem is the lack of information about the plot sizes that were used at the nine locations. The MMF and rMMF models are independent of slope length, but this is not the case for the hMMF. The surface runoff values calculated in mm's by the hMMF are independent of the slope length as long as $SR_i^{inf} = 0$, and will give exactly the same amounts as the rMMF, keeping all variables the same. For soil loss calculations this is not the case as the soil loss may increase with increasing slope length, depending on the slope shape. Unfortunately, also the information about the slope shape was not provided either, and in the hMMF calculations it was assumed that all slopes have a linear shape and a slope length of 22.1 m, similar to the length of the standard USLE erosion plot.

The hMMF calculations used the input variable values for *P*, P_o, *A*, *I*, *MS*, *BD*, *S*, *Et*/*Eo*, *K* and *C* as provided by Morgan and Finney (1982). Other input variables (*CC*, *PH* and *GC*) were estimated based on the provided crop types. No surface infiltration ($SR_i^{inf} = 0$) was assumed. Two types of hMMF simulations were made. In the first simulation, the recommended values (Morgan, 2005) for the input variables *EHD* and *COH*, and 1.5 for β were used. In the second simulation the values of *EHD* and β were calibrated to optimize the surface runoff and soil loss calculations.

The simulations results are provided in Table B1. Overall, the hMMF model with recommended values (hMMF rec.) performed less good as the rMMF model in Morgan (2001). The Nash-Sutcliffe Efficiency (NSE) for surface runoff is 0.55 for rMMF, while for the hMMF using recommended values it is 0.11. This is surprising as Morgan (2001) has used the same data, but his surface runoff amounts are closer to the measured values. If Morgan (2001) has used the same *P*, P_o, *MS*, *BD*, *S* and *Et*/*Eo* values as provided in Morgan and Finney (1982), it can only mean that Morgan (2001) has used different *EHD* values than the ones that are recommended by Morgan (2005). In many cases (e.g., Taiwan) the hMMF using the recommended *EHD* values largely underestimates the measured amounts. However, in a few cases (e.g., Lusotho, Tanzania) the calculated values of surface runoff match the measured values quite well.

For soil losses the hMMF using recommended values performed even less good than the rMMF. The NSE values are 0.56 for the rMMF and −0.06 for hMMF. There are several reasons for this poorer performance. The general underestimation of surface runoff results in low sediment transport amounts, and thus an underestimation of the soil losses as well. Moreover, the slope length used in the calculations (22.1 m) may not be correct for all sites which may introduce more errors.

During the second hMMF simulations (hMMF calib.) the *EHD* and β values were calibrated to match the measured surface runoff and soil loss values as good as possible. The NSE values are 1.00 for surface runoff and 0.73 for soil loss. This shows that the hMMF is well capable to simulate measured erosion values, but the recommended input variable values, especially *EHD*, may not be sufficiently accurate. In general the *EHD* values recommended by Morgan (2005) are too large and lead to underestimation of the surface runoff amounts. This underestimation subsequently results in often too low soil erosion amounts.

Table B.1
Comparison of measured, rMMF and hMMF modelled surface runoff and soil loss values.

Site	Surface runoff				Soil loss			
	Measured	rMMF	hMMF rec.	hMMF calib.	Measured	rMMF	hMMF rec.	hMMF calib.
	mm	mm	mm	mm	kg m^{-2}	kg m^{-2}	kg m^{-2}	kg m^{-2}
Lusotho, Tanzania								
Clay, maize/beans intercropped	0.2–1.0	12–19	0.3–0.7	0.2–1.0	0.001	0.005–0.014	0.000	0.000
Sandy Clay loam, evergreen forest	2.6–5.7	46–79	2.6–6.0	2.6–5.7	0.001–0.003	0.002–0.005	0.000	0.000
Sandy Clay loam, evergreen forest, steep slope	8.5–15	51–88	3.3–7.3	8.5–15	0.001–0.003	0.004–0.013	0.000	0.000
Clay, maize/beans intercropped, steep slope	0.4–0.8	1.1–12	0.3–0.7	0.4–0.8	0.001	0.000–0.012	0.000	0.000

(continued on next page)

Table B.1 (*continued*)

Site	Surface runoff				Soil loss			
	Measured	rMMF	hMMF rec.	hMMF calib.	Measured	rMMF	hMMF rec.	hMMF calib.
	mm	mm	mm	mm	kg m^{-2}	kg m^{-2}	kg m^{-2}	kg m^{-2}
Adiopodoume, Ivory Coast								
Sandy loam, secondary tropical forest	15	316	30	15	0.001–0.020	0.046	0.000	0.000
Sandy loam, bare soil	707–1415	1142	1337	1022	6.90–15.0	17.5	10.3	10.2
Sandy loam, oil palm	43–172	333	58	108	0.001–0.050	0.77	0.001	0.003
Sandy loam, banana with mulch	11–86	385	56	49	0.004–0.005	0.021	0.000	0.000
Sandy loam, maize	643–1608	617	248	1126	3.50–13.1	8.85	0.089	7.8
Sandy loam, groundnut	579–1565	731	332	1072	5.90–12.0	3.09	0.232	6.7
Sefa, Senegal								
Loam, secondary tropical forest	1.6–19	400	71	10	0.002–0.020	0.006	0.000	0.000
Loam, groundnut	130–699	723	276	415	0.29–1.63	2.43	0.042	1.1
Loam, cotton	15–699	646	429	357	0.05–1.85	4.17	0.126	0.619
Loam, maize	504	639	321	504	1.03	1.62	0.024	0.840
Loam, sorghum	390–683	660	341	537	0.33–1.24	3.48	0.057	0.610
Pong Khrai, Thailand								
Clay loam, upland rice	22–32	102	17	27	1.4–2.4	2.20	0.000	0.001
Clay loam, upland rice, bench terraces	16–53	84	12	35	1.1–1.3	0.63	0.000	0.001
Marchiazza Basin, Italy								
Loamy sand, bare soil with tufted grass	201–261	341	138	231	2.7–3.1	4.14	0.072	1.3
Loamy sand, Molinia moor grass	51–58	112	33	55	0.05–0.09	0.02	0.000	0.000
Loamy sand, chestnut and oak trees	36–38	92	2.8	37	0.009–0.018	0.005	0.000	0.000
Taiwan								
Clay loam, citrus, clean cultivation	1268	654	118	1268	15.6	16.34	0.043	15.5
Clay loam, citrus, bench terracing	344	543	94	344	0.50	8.25	0.041	0.48
Clay loam, citrus with mulch	109	360	59	109	0.094–0.28	0.07	0.000	0.003
Clay loam, banana, clean cultivation	1113–1449	346	1.5	1279	3.94–6.37	8.27	0.000	5.00
Clay loam, banana with mulch	189	257	1.0	190	0.009	0.015	0.000	0.009
Clay loam, banana with contour bunds	483–1029	346	1.0	757	0.11–0.39	0.22	0.000	0.28
Mpwapwa, Tanzania								
Sandy loam, bare soil	446	390	436	446	14.7	6.64	0.795	5.0
Sandy loam, sorghum and millet	80–259	141	2.1	170	5.5–9.0	0.61	0.000	0.114
Sandy loam, tufted grass	8–65	110	0.9	37	0.0–0.07	0.07	0.000	0.002
Sandy loam, savanna grass	3–4	59	0.2	4	0.0	0.002	0.000	0.000
Lyamungu, Tanzania								
Clay loam, coffee, clean cultivation	15–232	166	12	125	4.3	1.36	0.000	0.079
Clay loam, coffee, cover crops	10–98	54	2.0	54	0.4	0.015	0.000	0.001
Clay loam, coffee, contour ridges	36	170	8.3	36	0.3	0.09	0.000	0.000
Clay loam, coffee, cover crops, contour ridges	27	54	1.2	27	0.1	0.005	0.000	0.000
Henderson, Zimbabwe								
Clay, maize	8–61	78	13	35	0.2–0.3	0.106	0.000	0.000
Clay, grass	8–26	61	8.7	17	0.05–0.1	0.016	0.000	0.000

Appendix C

hMMF application at 30-m hillslope in Hungary: surface runoff infiltration

For this application, the 30-m bare soil slope of Hudek and Rey (2009) was used. The simulation of surface runoff and sediment transport along the hillslope without any surface runoff infiltration is shown in Fig. 1a, and copied here in Figure C1a. Figures C1b-d show the same hillslope simulation with different degrees of infiltration of surface runoff. The SR_i^{inf} values corresponding to Figures C1a-d are provided in Table C1. It was assumed that on top of the slope there is little surface runoff and thus also no or negligible infiltration. But as the layer of water builds up in downslope direction the hydraulic head increases, which may lead to increased infiltration of surface runoff (Langhans et al., 2014).

The surface runoff profiles of Figure C1 show that the profiles become curved and result in less surface runoff from the slope. The simulated values of surface runoff decrease from 383 mm in Figure C.1a to 198 mm in Figure C1d. The intermediate values are 330 mm and 269 mm in Figures C.1b and C.1c, respectively. Notwithstanding the difficulties in quantifying actual amounts of infiltration of surface runoff, the profiles presented in Figure C1c and C.1d show much similarity with experimental surface runoff profiles as presented in Sheridan et al. (2014). Inclusion of surface runoff infiltration leads therefore to a more realistic surface runoff profile, but the values of the SR_i^{inf} variable remain largely unknown for actual infiltration levels on a natural hillslope.

Inclusion of surface runoff infiltration in the hillslope hydrology leads to lower sediment transport and soil losses (Figure C1). The actual soil loss from the plot was 2.20 kg m^{-2} and the simulated value was 2.21 kg m^{-2} in the case without surface runoff infiltration (Figure C1a). With surface runoff infiltration the soil loss values drop to 1.51 kg m^{-2} (Figure C.1b), 0.90 kg m^{-2} (Figure C.1c) and 0.42 kg m^{-2} (Figure C1d). The sediment transport is transport capacity limited in all three cases with surface runoff infiltration.

Table C.1
Values of SR_i^{inf} variable used in hMMF model simulations of the bare soil plot at Szentendre, Hungary (Hudek & Rey, 2009).

Slope section	SR_i^{inf}			
m	Fig. C1a	Fig. C1b	Fig. C1c	Fig. C1d
0–3	0	0	0	0
3–6	0	0	0	0
6–9	0	0.01	0.03	0.03
9–12	0	0.01	0.03	0.06
12–15	0	0.02	0.05	0.09
15–18	0	0.02	0.05	0.12
18–21	0	0.03	0.07	0.13
21–24	0	0.03	0.07	0.14
24–27	0	0.04	0.09	0.15
27–30	0	0.04	0.09	0.16

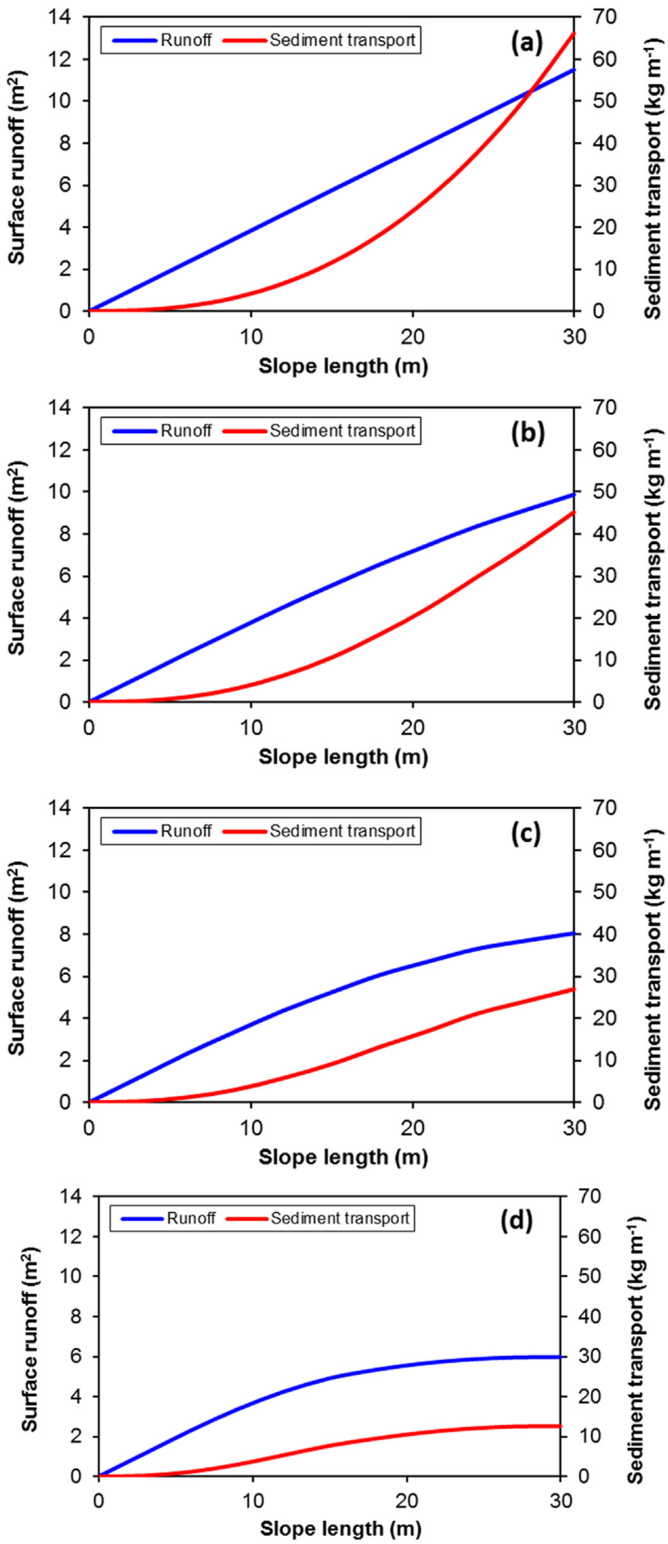

Fig. C.1. The influence of surface runoff infiltration on surface runoff amount and sediment transport along a 30-m hillslope at Szentendre, Hungary. Surface runoff infiltration has been accounted for with the SR_i^{inf} variable in the hMMF model. Values of SR_i^{inf} used in Figures (a), (b), (c) and (d) are provided in Table C1.

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