Natural Hazards **19:** 47–77, 1999.

Empirical Relationships for Debris Flows

DIETER RICKENMANN
Swiss Federal Institute for Forest, Snow and Landscape Research, CH-8903 Birmensdorf, Switzerland (phone: +41 1 739 24 42; fax: +41 1 739 24 88; e-mail: rickenmann@wsl.ch)

(Received: 18 September 1998; in final form: 2 February 1999)

Abstract. The assessment of the debris flow hazard potential has to rely on semi-quantitative methods. Due to the complexity of the debris-flow process, numerical simulation models of debris flows are still limited with regard to practical applications. Thus, an overview is given of empirical relationships that can be used to estimate the most important parameters of debris-flow behavior. In a possible procedure, an assessment of a maximum debris-flow volume may be followed by estimates of the peak discharge, the mean flow velocity, the total travel distance, and the runout distance on the fan. The applicability of several empirical equations is compared with available field and laboratory data, and scaling considerations are used to discuss the variability of the parameters over a large range of values. Some recommendations are made with regard to the application of the presented relationships by practicing engineers, apart from advocating field reconnaissance and searching for historic events wherever possible.

Key words: Debris-flow volume, peak discharge, flow velocity, travel distance, runout distance, hazard assessment, torrent, debris flow.

Notation

B	width of the breach;
C	Chezy coefficient;
C_1	constant in flow resistance equation;
C_2	constant in general velocity Equation (20);
d_{90}	characteristic grain size for which 90% of the bed material is finer in diameter;
g	gravitational acceleration;
H	flow depth;
H_e	elevation difference between the starting point and the lowest point of deposition of the mass movement;
H_r	height of the temporary reservoir;
K_1	constant in dambreak Equation (9);
L	total travel distance, of a debris flow or mass movement;
L_f	runout distance on the fan, of a debris flow or mass movement;
M	debris-flow volume (event magnitude);
M_w	volume of water (behind a dam);
N	number of observations;

n Manning coefficient;
Q discharge (of debris flow or flood);
Q_p peak discharge;
q_p unit peak discharge;
S channel slope;
V mean flow velocity;
α exponent of H in general velocity Equation (20);
β exponent of S in general velocity Equation (20);
μ dynamic viscosity of the grain-water mixture;
ρ density of the grain-water mixture;
ξ lumped coefficient in dilatant grain shearing.

Subscript
$*$ denotes the ratio of two quantities of the same kind but of different size.

1. Introduction

Debris flows are a phenomenon intermediate between landslides or rockfalls and fluvial sediment transport. Debris flows most often occur as a result of intense rainfall but there are also other triggering mechanisms such as snowmelt or dam-break failure (e.g., Costa, 1984). In a torrent catchment, debris flows often produce much higher peak discharges than "ordinary" floods under the same rainfall conditions. The peak discharges often exceed channel capacities on the fan, resulting in widespread sediment deposition on the fan and associated hazard to buildings, infrastructure and people.

Observations of debris flows have been reported for many decades. Systematic research into the mechanics of these flows started about 30 years ago, including detailed investigations in hydraulic laboratories. At the beginning, basically three simple fluid models were proposed to treat debris flows (see, for example, Costa, 1984; Hungr *et al.*, 1984): Newtonian flow (in the turbulent or laminar regime), Bingham fluid flow (laminar regime), and dilatant grain shearing flow (mostly considered in the inertial regime). A comprehensive account of the physics of debris flows has been presented recently by Iverson (1997).

In order to perform a hazard assessment on a fan and eventually to design protective measures against debris flows, it is necessary to estimate the important parameters such as potential debris volume, mean flow velocity, peak discharge, and runout distance. In several studies, simple empirical relationships have been proposed to estimate these parameters (e.g., Hungr *et al.*, 1984; Costa, 1984; Johnson, 1984; PWRI, 1988). The verification of the validity and the limits of these relationships is difficult mainly for three reasons: (i) the variety of material composition may limit the applicability to a narrow range; (ii) the number of field observations is rather limited; and (iii) replication of debris flows in laboratory studies is difficult because the scaling laws are more complex than, for example, for clear-water open-channel flows.

The objective of this paper is to give an overview of a possible procedure for roughly estimating the most important parameters related to the debris-flow hazard in a torrent catchment. It is recognized that knowledge about past debris-flow activity is a very important source of information which should be taken into account – if available – in any hazard assessment. The interpretation of past evidence (Aulitzky, 1980; Costa, 1988a; Nakamura, 1980) is not discussed here. The focus is on the comparison of different empirical relationships with field observations.

2. Hazard Assessment

Rickenmann (1995) proposed a method for the evaluation of debris-flow hazards in a particular torrent catchment composed of two steps:

1. Determination of the probability that a debris flow event can occur in the torrent catchment under consideration.
2. Quantitative estimation of the most important parameters useful for a hazard assessment.

At present, there are no rigorous methods which would allow a strict assessment to determine an exact probability of debris-flow occurrence, be it based either on physically measured characteristics of a catchment or on a statistical analysis. If there is information available on past debris flow events, this is often the most reliable indication. It is noted that the concept of 'recurrence intervals', as borrowed from flood frequency analysis, may be problematic when applied to debris flow events (Davies, 1997). For example, temporary storage of sediments may be of importance, and thus an event may depend on previous ones. If information on historic events is available, it may be possible to determine a characteristic pattern between debris flow frequency and debris-flow volume for a particular catchment; this pattern has been found to depend on the sediment availability and on the lithology of the catchment (Zimmermann *et al.*, 1997a, b).

Semi-quantitative methods which allow one to estimate the likelihood of debris flow occurrence in a particular torrent catchment have been proposed in Austria (Aulitzky, 1973, 1980, 1984), in Japan (Nakamura, 1980), and in Canada (VanDine, 1985). In these evaluations, factors such as previous debris-flow traces, sediment sources and erodibility, channel slopes, infiltration capacity and others are weighted and combined to arrive at an index value which represents a combined degree of probability and event magnitude of a possible debris flow. Based on the analysis of numerous debris-flow events which occurred in Switzerland in the summer of 1987 (Rickenmann and Zimmermann, 1993), a similar approach has been proposed to estimate the likelihood of possible debris-flow activity in a torrent catchment in the absence of any knowledge about past events (Rickenmann, 1995). In this procedure, the slope of the torrent channel in the possible initiation zone and the sediment source potential are considered to be the two most important factors.

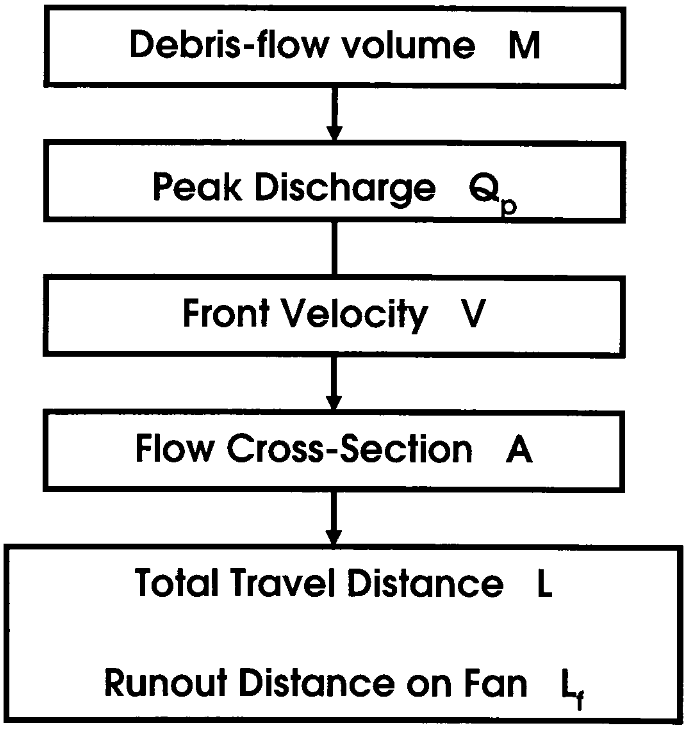

Figure 1. Flow chart for estimating debris flow parameters with the help of empirical formulae.

The second major step in a debris-flow hazard assessment is based on a quantitative estimation of the most important parameters needed to delineate endangered areas. A number of empirical formulae may be used for this purpose. The flow chart in Figure 1 illustrates a possible procedure using some of the empirical equations discussed below.

As an alternative one may also consider using a numerical simulation model to assess the flow properties and the depositional behavior (e.g., Hungr, 1995). In most models, the water-solids mixture of a debris flow is assumed to be a single component fluid with particular rheologic characteristics, and mainly three types of constitutive equations were used to derive a flow resistance law: Bingham laminar flow, Newtonian turbulent flow, or dilatant grain shearing in the inertial regime. A comparison of simple model approaches has recently been made by Rickenmann and Koch (1997) and Koch (1998). In general, these models have been applied only to very few field cases.

3. Empirical Relationships

3.1. DEBRIS-FLOW VOLUME

From the point of view of the evaluation of a potential hazard, the debris-flow volume, M, is one of the most important parameters. In general, a spectrum of possible debris-flow volumes can be expected to occur with different probabilities. However, often an acceptable recurrence interval with an associated event magnitude has to be defined when designing any protection measures. As a rough approximation, the debris-flow volume can then be used to arrive at an estimate of the associated peak discharge, Q_p, the total travel distance, L, and also the runout distance on the fan, L_f (e.g., Ikeya, 1989; Mizyuama *et al*., 1992; Schilling and Iverson, 1997).

Many attempts have been made to estimate a maximum debris-flow volume for a given torrent catchment. These empirical equations are usually based on the most important morphometric characteristics of a catchment (e.g., Hampel, 1977; Takei, 1980; Kronfellner-Kraus, 1984, 1987; Zeller, 1985; Rickenmann and Zimmermann, 1993; D'Agostino, 1996). With about 200 observations on debris-flow volumes, M, an analysis was made using some of these empirical equations. Due to lack of more data, the analysis considered only the most important morphometric catchment characteristics. It is found that these equations may overestimate the actual debris-flow volume by up to a factor of 100. It is therefore recommended to make a geomorphologic assessment of the sediment potential rather than using these equations. Some of the empirical relationships also include information on expected rainfall conditions or on the lithologic characteristics of the catchment. It is likely that a more detailed analysis, considering a subdivision of torrent catchments according to lithologic units which are possibly contributing to the total sediment yield, may lead to more accurate estimates.

3.2. PEAK DISCHARGE

Knowledge of the peak discharge and the associated flow velocity are important when evaluating the conveyance capacity of stream channel reaches or critical cross-sections as, for example, under bridges. It has been shown that empirical relationships can be established between the peak discharge, Q_p, of a debris flow and the debris-flow volume (Hungr *et al*., 1984; Mizuyama *et al*., 1992; Takahashi *et al*., 1994).

In Figure 2, data of Table I on peak discharge and debris-flow volume are shown. Also plotted is a semi-theoretical line which is derived from the assumption that Froude scaling must be satisfied for flows of different size but having essentially the same physical properties. The corresponding equation has the following form:

$$Q_* = 0.1 M_*^{5/6} = 0.1 M_*^{0.833}, \quad (1)$$

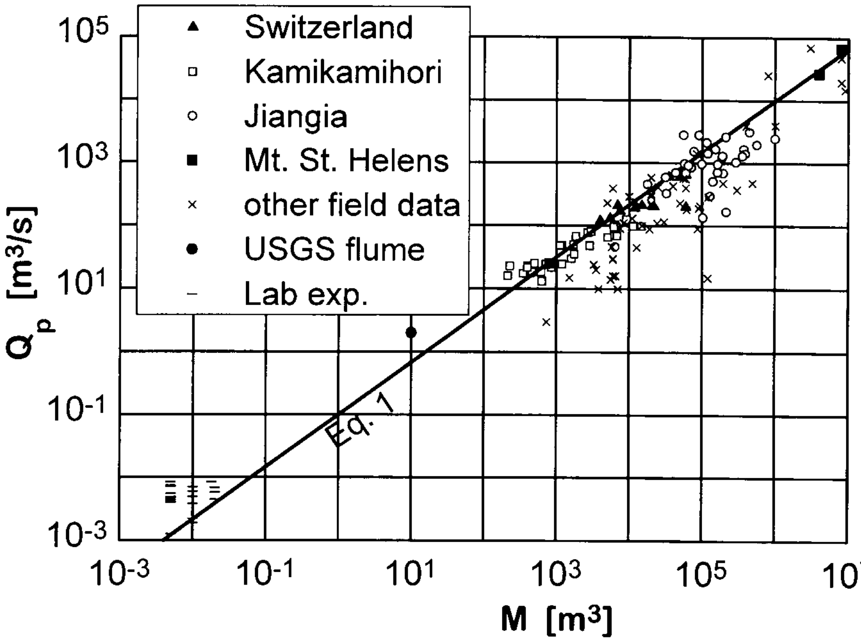

Figure 2. Peak discharge (Q_p) of debris flows vs debris-flow volume (M). Also shown is the semi-theoretical line satisfying Froude similarity (Equation (1)).

where $Q_* = Q_{p2}/Q_{p1}$ and $M_* = M_2/M_1$, and the indices 1 and 2 refer to two flows of similar material properties but of different size. The derivation of Equation (1) is given in the Appendix. The constant $A_1 = 0.1$ has been approximated for a line representing on average the higher peak discharges of the field debris flows shown in Figure 2. In the tables, N refers to the number of observations used in the analysis.

It has been proposed by Mizuyama *et al.* (1992) that different empirical relationships exist for granular and for muddy type debris flows in Japan. This statement is supported by other empirical equations listed in Table II, and the corresponding lines shown in Figure 3. The following notation is used in Table II: In all equations Q_p is in [m^3/s] and M or M_w is in [m^3], where M_w is the volume of water stored behind the dam. When comparing debris flows with dambreak floods, it is noted that the outflowing water may incorporate sediments which can result in a bulking of the total volume up to about a factor of two for glacier lake outburst floods (Haeberli, 1983). However, this distinction is not considered important here since the scatter of debris-flow data in the empirical relationships usually covers at least one order of magnitude.

The data presented in Figure 2 pertain predominantly to granular type debris flows. An upper limit for this data is also approximated by the line for granular type debris flows from Japanese data, Equation (2), shown in Figure 3. From this figure one can see that the data representing mudflows, Equation (3), and those

Table I. Data on debris-flow volume and peak discharge of debris flows, used in Figure 2

Country/Region	N	M [m^3]	Q_p [m^3/s]	Source
Swiss Alps	11	4,000–60,000	120–650	Rickenmann & Zimmermann (1993); M. Zimmermann, written comm. (1996)
Canadian Cordillera	23	1500–3,000,000	10–70,000	Hungr *et al.* (1984); VanDine (1985); M. Jakob, written comm. (1995)
Japan (Kamikamihori valley)	26	214–14,800	13–124	Okuda & Suwa (1981); H. Suwa, written comm. (1997)
China, Jiangia	33	400–999,000	46–3133	M. Jakob, written comm. (1995); Z. Wang, written comm. (1997)
USA, Mount St. Helens	3	810–8,000,000	25–68,000	Pierson (1985); Pierson (1986)
Other field data (incl. lahars)	22	6,000–70,000,000	15–48,000	Several sources**
USGS flume	1	10	2	Iverson & LaHusen (1993)
Laboratory flows	26	0.005–0.02	0.00126–0.0102	Davies (1994)
Overall	*145*	*0.005–70,000,000*	*0.00126–68,000*	

** Arattano *et al.* (1996), Aulitzky (1970), Gallino & Pierson (1985), Han & Wang (1996), Harris & Gustafson (1993), Kermculov & Zuckerman (1983), Pierson (1980), Pierson (1995), Rutherford *et al.* (1994), Watanabe & Ikea (1981), Webb *et al.* (1988).

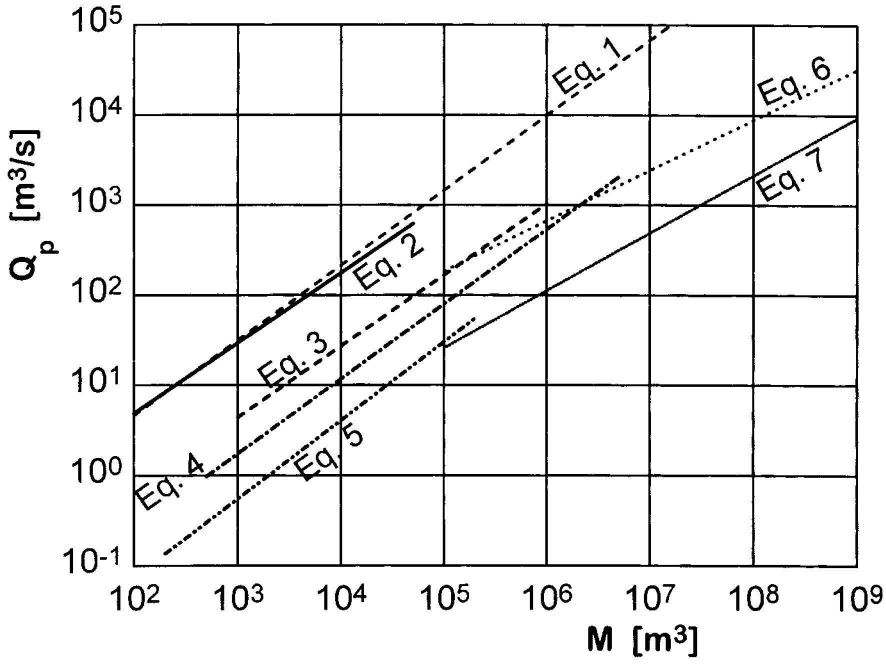

Figure 3. Empirical relationships of peak discharge (Q_p) of debris flows (Equations (2) to (5)) or dam failures (Equations (6) and (7)) vs debris-flow volume (M). Also shown is the semi-theoretical line satisfying Froude similarity (Equation (1)).

Table II. Empirical formulae to estimate the peak discharge as a function of the debris-flow volume of debris flows or of the stored water of a dambreak flood. The correlation coefficients r^2 are those given by the authors; 'nn' indicates that r^2 is not known

Data basis	Formula	Equation	N	r^2	Source
Granular debris flows (Japan)	$Q_p = 0.135\ M^{0.780}$	(2)	~50	nn	Mizuyama *et al*. (1992)
Muddy debris flows (Japan)	$Q_p = 0.0188\ M^{0.790}$	(3)	~100	nn	Mizuyama *et al*. (1992)
Merapi volcano (Indonesia)	$Q_p = 0.00558\ M^{0.831}$	(4)	~200	0.95	Jitousono *et al*. (1996)
Sakurajima volcano (Japan)	$Q_p = 0.00135\ M^{0.870}$	(5)	~100	0.81	Jitousono *et al*. (1996)
Landslide dam failures	$Q_p = 0.293\ M_w^{0.56}$	(6)	9	0.73	Costa (1988b)
Glacial dam failures	$Q_p = 0.0163\ M_w^{0.64}$	(7)	20	0.80	Costa (1988b)

representing volcanic debris flows with predominantly fine material, Equations (4) and (5), clearly have smaller peak discharges for a given debris-flow volume than the granular type debris flows. It is observed that the exponents of the empirical Equations (2) to (5) defined by the field data are quite close to the exponent required from Froude scaling as given in Equation (1). It is also interesting that the Mount St. Helens data lie quite close to Equation (1) in Figure 2, including flows of very different magnitude but being composed of essentially the same material. The data referring to landslide and glacial dam failures, Equations (6) and (7), are generally associated with flow surges containing large amounts of water (apart from the eroded solid material). The data of these flows lie closer to those debris flows containing more fine than coarse material.

It is noted that in a more physically strict sense the peak discharge of a debris flow surge should be related to the debris-water volume of the corresponding surge and not to the total debris-flow volume. Unfortunately, this more precise volume is not known in many cases; in order to use as many observations as possible, such cases have been included nevertheless here. For a given debris-flow volume and material characteristics, the peak discharge may also depend to some extent on initial and boundary conditions.

A comparison can also be made with the dambreak formula, from which the peak discharge immediately downstream of the breach can be estimated as (Hungr *et al*., 1984):

$$Q_p = 0.30 B g^{1/2} H_r^{3/2}, \tag{8}$$

where B is the width of the breach, H_r the height of the temporary reservoir, and g the gravitational acceleration. Assuming that $B \sim H_r^{0.5}$ (i.e., a parabola shaped cross-section) and that the water volume behind the temporary dam is $M_w \sim H_r^{2.5}$, one can express the peak discharge as

$$Q_p = K_1 M_w^{0.80}, \tag{9}$$

where K_1 is a constant depending on the geometry of the temporary reservoir. A more sophisticated analysis of the dambreak problem is given in Walder and

O'Connor (1997). According to this analysis Equation (8) is approximately valid if no significant drawdown of the lake water level occurs. Nevertheless, it is interesting to note that the empirical Equations (2) to (5) show a similar dependence of Q_p on M as Q_p on M_w in Equation (9) based on the dambreak assumption.

3.3. MEAN FLOW VELOCITY

In order to describe the flow behavior of debris flows, a number of approaches and flow resistance equations have been proposed. To evaluate constitutive equations for the shear behavior of different debris-flow materials, knowledge of the velocity profile would be very helpful (but insufficient). However, such information is very difficult to obtain for actual debris-flow material in the field. Most of the proposed flow-resistance equations for the mean velocity are based either on empirical data of mean flow parameters of prototype flows or measured velocity profiles in laboratory flows, in which simplified material mixtures have been used to simulate debris flows.

Most observations are available for either the mean translational velocity of the frontal part or the maximum (mean cross-sectional) velocity along the debris flow surge (here maximum refers to the variation of the mean velocity along the debris flow wave). It is noted that the maximum velocity of a surge does not necessarily coincide with the part of the wave where the maximum flow depth occurs (e.g., Suwa *et al.*, 1993). In the following analysis, the possible noncoincidence between the location of maximum flow depth and maximum velocity is neglected, as well as the distinction between mean velocity at a cross-section and mean translational velocity.

A comparison is made of different approaches which have been proposed to estimate the maximum (mean cross-sectional) velocity of the frontal part of debris flows (e.g., Hungr *et al.*, 1984). The proposed equations are summarized in Table III. There the following notation is used: V [m/s] is the (cross-sectional mean) flow velocity, H [m] is the (maximum) flow depth, S is the channel bed slope, ρ [kg/m^3] is the density of the grain-water mixture, μ [kg/(sm)] is the dynamic viscosity of the grain-water mixture, ξ [1/(sm$^{1/2}$)] is a lumped coefficient depending on grain size and grain concentration, n [s/m$^{1/3}$] is the Manning coefficient, C_1 [m$^{1/2}$/s] is the Chezy coefficient, and C_1 [m$^{0.7}$/s] is a dimensional empirical coefficient.

Most of the models listed in Table III have been proposed in previous studies to estimate the mean velocity, V, of debris flows (e.g., Hungr *et al.*, 1984; Hungr, 1995). In the application of these equations to the data of Table IV, flow depth is used rather than the hydraulic radius, since for the available data there is often not sufficient information to determine the hydraulic radius. It is noted that the laminar flow Equation (10) approximates Bingham fluid flows for larger flow velocities and lower Bingham yield stresses (as compared to bed shear stress). In Equation (10) the constant 1/3 is valid for a wide rectangular channel, but depends on the flow cross-section in general. Equation (11) represents the Bagnold type relationship for

Table III. Equations proposed to estimate the mean velocity of debris flow surges

Flow type	Formula	Equation
Newtonian laminar flow	$V = (1/3)\rho g H^2 S/\mu$	(10)
Dilatant grain shearing	$V = (2/3)\xi H^{1.5} S$	(11)
Newtonian turbulent flow: Manning–Strickler equation	$V = (1/n) H^{2/3} S^{1/2}$	(12)
Newtonian turbulent flow: Chézy equation	$V = C H^{1/2} S^{1/2}$	(13)
Empirical equation	$V = C_1 H^{0.3} S^{0.5}$	(14)

dilatant grain shearing in the inertial regime, which is also the basis of Takahashi's (1991) debris-flow model, and the constant 2/3 is valid for a wide rectangular channel. The Manning–Strickler Equation (12) has been proposed for debris flows in Japanese guidelines (PWRI, 1988). The Chézy Equation (13) is used in the Voellmy approach to estimate the flow parameters of wet snow avalanches, and this approach has also been applied to debris flows (Rickenmann, 1990). The empirical Equation (14) has been found to give good results in numerical simulations of unsteady debris-flow surges (Koch, 1998).

Using data on debris-flow observations listed in Table IV, the 'flow-resistance coefficients' or 'material parameters' of Equations (10) to (14), i.e., μ, ξ, n, C, C_1, are backcalculated and shown in Figures 4(a–c) as a function of the peak discharge. Also shown in the same Figures are the semi-theoretical relationships based on the assumption of Froude scaling. The corresponding equations are listed in Table V and their derivation is included in the Appendix. The intercepts of the lines in Figures 4(a–c) have been approximated in order to represent roughly a mean value of the available data.

Equations (10) to (14) can be expressed in the following general form:

$$V = C_2 H^{\alpha} S^{\beta}, \tag{20}$$

where C_2 is an empirical constant depending on the values of α and β. It is observed from Figures 4(a–c) that the scatter of the flow resistance coefficient about the scaling relationship is reduced as the sum of the exponents α and β in Equation (20) gets smaller within the examined range. In Figures 4(a–c), the scatter about the semi-theoretical relationship is about a factor of 100 for the Newtonian laminar flow resistance coefficient, Equations (10) and (15), respectively, and decreases to about a factor of 10 for Equations (14) and (19), respectively. In Figures 4(b) and (c), 272 data points obtained for the mean velocity of clear water flows in torrents and gravel-bed rivers (Rickenmann, 1994, 1996) have also been included for further comparison. The characteristics of the data on clear water flows are

Table IV. Data on mean flow velocity of debris flows, used in Figures 4(a–c), 5(a, b), 6. The following methods were used to determine V and H: US = ultrasonic flow depth records at two cross-sections; WS = electric wire sensors at two cross-sections; RV = Radar velocitymeter; SE = superelevation of flow surface in bends; VA = analysis of video pictures; BS = belt speed; QA = determination from measured flow rate and flow cross-section; nn = not known, presumably QA type measurement. The ranges indicate the maximum and minimum value within each sub-dataset

Country/Region	N	Q_p [m^3/s]	V [m/s]	S	H [m]	Type of measurement	Source
Dataset A: 'small-scale' field debris flows, precise measurements							
Italy, T. Moscardo	7	3–88	0.9–5	0.11	0.84–2.17	US	Arattano *et al*. (1996)
Japan, Kamikamihori valley	12	24–124	1.9–6.4	0.09	1.5–4.1	WS	Okuda & Suwa (1981); H. Suwa, written comm. (1997)
U.S.A., Mt. St. Helens (Shoestring Site)	6	0.012–25	0.8–4.4	0.12–0.4	0.05–2.8	US	Pierson (1986)
Dataset B: 'large-scale' field debris flows, precise measurements							
China, Jiangia gully	33	46–3133	4–14.5	0.05–0.073	0.6-5.5	US, RV	M. Jakob, written comm. (1995); Z. Wang, written comm. (1997)
Dataset C: 'small-scale' field debris flows, indirect measurements							
Swiss Alps	29	15–640	3.5–14	0.07–0.53	1–10	SE	VAW (1992); M. Zimmermann, written comm. (1996)
Dataset D: 'large-scale' field debris flows, indirect measurements							
U.S.A., Mt. St. Helens (Pine C. + Muddy R.)	20	2,400–66,800	3–28	0.003–0.15	2–21	SE	Pierson (1985)
Columbia, Nevado del Ruiz	17	710–48,000	5–17	0.009–0.17	2–25	SE	Pierson *et al*. (1990)
Dataset E: laboratory debris flows, precise measurements							
Laboratory flume, Jiangia material China	30	0.001–0.100	0.21–3.77	0.053–0.19	0.04–0.13	nn	Wang & Zhang (1990)
Laboratory flume, New Zealand New Zealand	26	0.001–0.010	0.12–0.65	0.11–0.27	0.06–0.19	VA	Davies (1994)
Laboratory flume, conveyor belt	12	0.001–0.002	0.37–0.58	0.17–0.34	0.04–0.08	BS	Davies (1990)
Laboratory flume, U.S.A.	14	0.0004–0.0017	0.54–1.51	0.37–0.42	0.006–0.013	QA	Garcia Aragon (1996)
Overall	*23–1*	*0.0004–68,000*	*0.12–31*	*0.003–0.53*	*0.006–25*		

Table V. Semi-theoretical relationships to express the 'flow resistance coefficient' as a function of the discharge, shown in Figures 4(a–c)

Flow type	Formula	Equation	In Appendix
Newtonian laminar flow	$\mu_* = 20Q_*^{3/5}$	(15)	(A8b)
Dilatant grain shearing	$\xi_* = 150Q_*^{-2/5}$	(16)	(A10b)
Newtonian turbulent flow: Manning–Strickler equation	$n_* = 0.077Q_*^{1/15}$	(17)	(A12b)
Newtonian turbulent flow: Chézy equation	$C_* = 22$	(18)	(A13b)
Empirical equation	$C_{1*} = 10\ Q_*^{2/25}$	(19)	(A15b)

Table VI. Data on mean velocity of clear water flows in torrents and gravel-bed rivers, used in Figures 4(b, c), 5(a), 6

Country	N	Q [m^3/s]	V [m/s]	S [%]	H [m]	Source
Dataset F						
Switzerland	94	0.021–2.89	0.15–0.95	0.9–63	–	Hodel (1993)
Switzerland	7	0.031–1.75	0.19–1.11	15–45	–	Rickenmann (1996)
Dataset G						
Austria	11	3.30–22.2	0.94–1.80	1.7–20.5	0.64–1.41	Ruf (1990)
Colorado, U.S.A.	69	0.340–128	0.27–2.64	0.2–3.9	0.15–2.01	Jarrett (1984)
England	41	0.137–103	0.17–3.72	0.5–3.8	0.10–1.31	Bathurst (1985)
New Zealand	5	60–140	1.85–3.13	5.2	0.79–1.09	Thompson & Campbell (1979)
Colorado, U.S.A.	12	2.05–10.5	0.52–1.42	1.4–2.0	0.30–0.64	Thorne & Zevenbergen (1985)
New Zealand	82	0.340–1540	0.22–3.32	0.0085–1.1	0.15–7.51	Griffiths (1981): without sediment transport
New Zealand	52	11.4–2410	0.86–4.31	0.083–0.71	0.34–3.97	Griffiths (1981): with sediment transport
Overall	*373*	*0.021–2410*	*0.15–4.31*	*0.0085–63*	*0.10–3.97*	

shown in Table VI (dataset G). A similar representation as in Figures 4(a–c) has also been made using the unit peak discharge q_p instead of the full peak discharge Q_p. Similar trends are found. Since the data set is less comprehensive when using q_p values, only the representation using Q_p values is shown here.

One may argue that the scatter for example in Figure 4(a) about the semi-theoretical scaling relationship for Newtonian laminar flow reflects different values

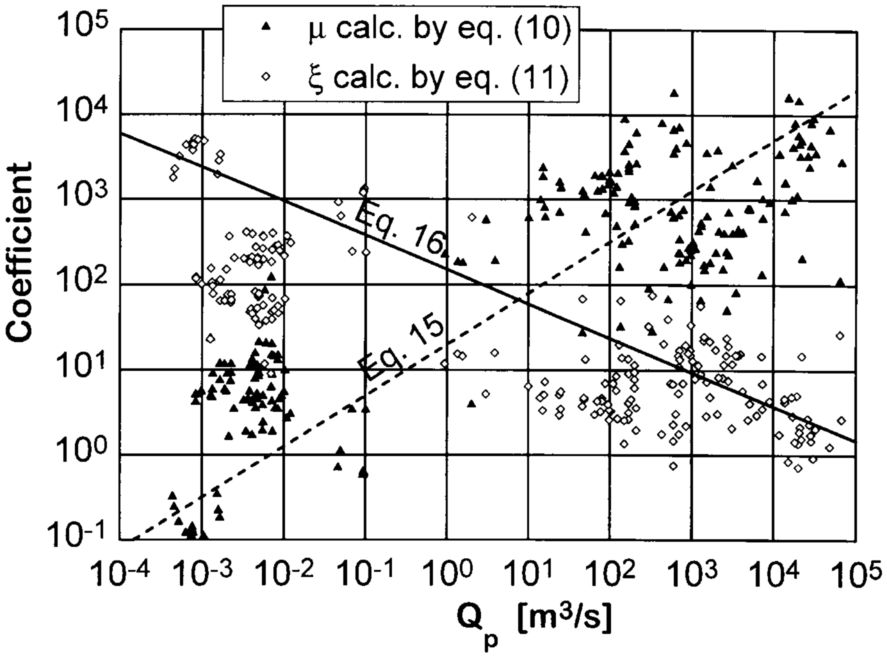

Figure 4a. Comparison of backcalculated 'flow resistance coefficient' vs peak discharge (Q_P) of debris flows with semi-theoretical relationship based on Froude scaling (Equations (15) and (16)). Shown are the dynamic viscosity μ for Newtonian laminar flow and the lumped ξ parameter for dilatant inertial flow.

for the viscosity of the debris-water mixture; it is known that the viscosity strongly depends for example on sediment concentration and the amount of cohesive fine material (e.g., Major and Pierson, 1992). On the other hand it is seen on Figure 4(b) that debris flow data show a similar scatter as the clear water data around the semi-theoretical scaling relationship for Chezy C or Manning's n. In absence of sufficient rheologic information, similar flow resistance laws valid for clear water flows may therefore be used to describe the mean flow behavior of debris flows. While for clear water flows C or n is primarily a function of the channel roughness, the respective flow-resistance parameters of debris flows might depend in addition to some extent on the mechanical properties of the mixture.

Costa (1984) reported some empirical equations for the mean velocity of debris flows from Russian, Chinese and Japanese studies. They are also of the form of Equation (20), and the exponents vary in the range $0.5 < \alpha < 0.67$ and $0.25 < \beta < 0.5$. The data base for these equations is different from the one listed in Table IV, and they therefore confirm the findings of this study. It may also be noted that a similar conclusion has been drawn from a comparison of different flow resistance equations implemented in a 1D numerical simulation model (Rickenmann and Koch, 1997; Koch, 1998). With this model, the unsteady flow behavior of debris-flow surges has been studied together with observations available for the

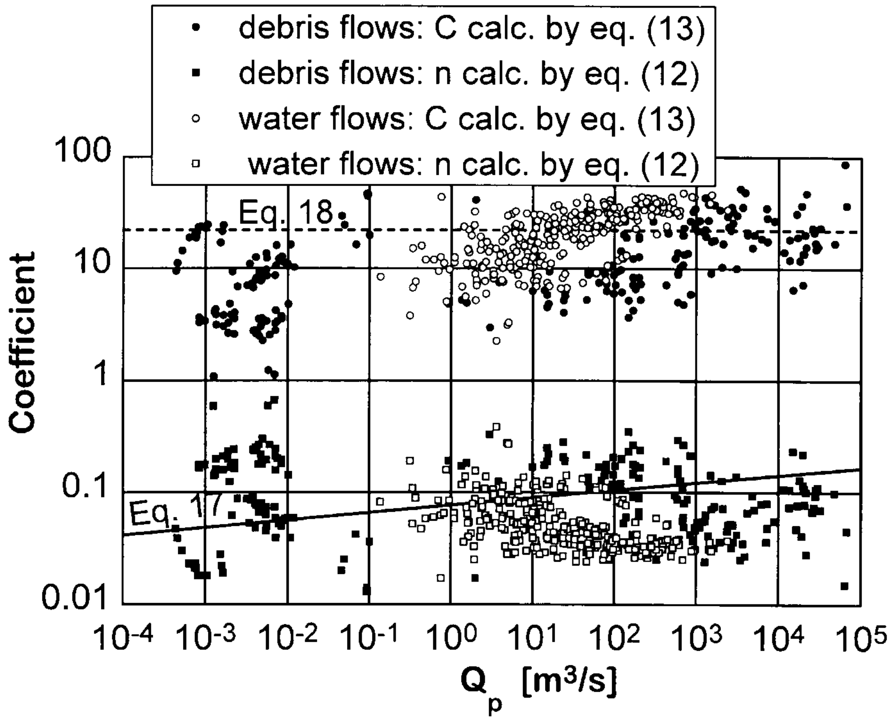

Figure 4b. Comparison of backcalculated 'flow resistance coefficient' vs peak discharge (Q_p) of debris flows and clear water flows with semi-theoretical relationship based on Froude scaling (Equations (17) and (18)). Shown are the Manning's n and the Chezy C for Newtonian turbulent flow.

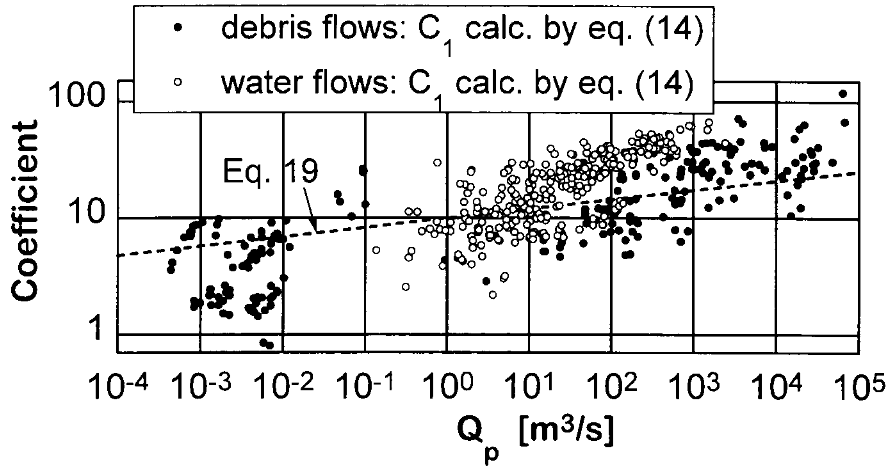

Figure 4c. Comparison of backcalculated 'flow resistance coefficient' C_1 vs peak discharge (Q_p) of debris flows and clear water flows with semi-theoretical relationship based on Froude scaling (Equation (19)). The coefficient C_1 is calculated by a new empirical equation.

Kamikamihori valley in Japan. It has been found that the observed flow behavior can be reasonably well simulated using a flow resistance approach as, for example, the Manning's or Chezy equation for clear water flow. (Using the laminar or dilatant flow resistance approach, the simulated flow behavior is much more sensitive to variations of the discharge and flow depth along the debris wave, and it is difficult or impossible to reproduce the observations with only one value for the flow resistance parameters; varying the resistance parameters μ and ξ along the debris wave may result in a better agreement with the observed flow behavior.)

It has also been proposed in other studies that the peak flow velocity of debris flows may be estimated using the Manning–Strickler Equation (12) with $n \approx 0.1$ s/m$^{1/3}$ (Pierson, 1986; PWRI, 1988; Rickenmann and Zimmermann, 1993). Figure 5(a) compares the application of Equation (12) to debris flows, with an average $n = 0.1$ s/m$^{1/3}$, and clear water flows, for which a mean value $n = 0.067$ s/m$^{1/3}$ has been used. The clear water data is listed in Table VI. (In Figure 5 the dataset F of Table VI is not included since there is no information on the flow depth.) The correlation coefficient and the standard error between calculated and observed velocities are shown in Table VII for different datasets of Table IV and Table VI. In Figure 5(b), the field debris flow datasets A, B, C, and D are shown separately. Dataset A shows the best correlation between calculated and observed flow velocities, while the scatter for the other datasets is rather large. However, a trend for a grouping of the datasets can be observed which appears to reflect a difference in scale and material composition. In other words Figure 5(b) implies that the coarser grained alpine type debris flows (set A and C) tend to require a higher value for n than the finer grained mudflows and lahars (set B and C). This trend is in general agreement with the grouping of the relationships between Q_p and M in Figure 3 and Table II. A somewhat similar conclusion can be made from the analysis of the surface velocity of debris flow surges in the Kamikamihori valley in Japan where the friction coefficient (similar to a Chezy value) decreases with increasing content of coarse gravel in the flow (Suwa *et al.*, 1993).

Analyzing clear water flows in torrents and gravel-bed rivers, an empirical equation has been developed where the mean flow velocity is expressed as a function of the discharge, Q, the slope, S, and the characteristic grain size d_{90}, for which 90% of the bed material is finer in diameter (Rickenmann, 1994, 1996, 1998). For the debris flow data of Table IV, there is not sufficient information on grain size distribution, therefore a simplified version of the equation is proposed here as follows:

$$V = 2.1 Q^{0.33} S^{0.33}. \quad (21)$$

Application of Equation (21) results in a reasonable agreement between calculated and observed velocities for debris flows, with a similar scatter as for clear water flows, as shown in Figure 6. Again, the correlation coefficient and the standard error between calculated and observed velocities are shown in Table VII for different datasets of Table IV and Table VI.

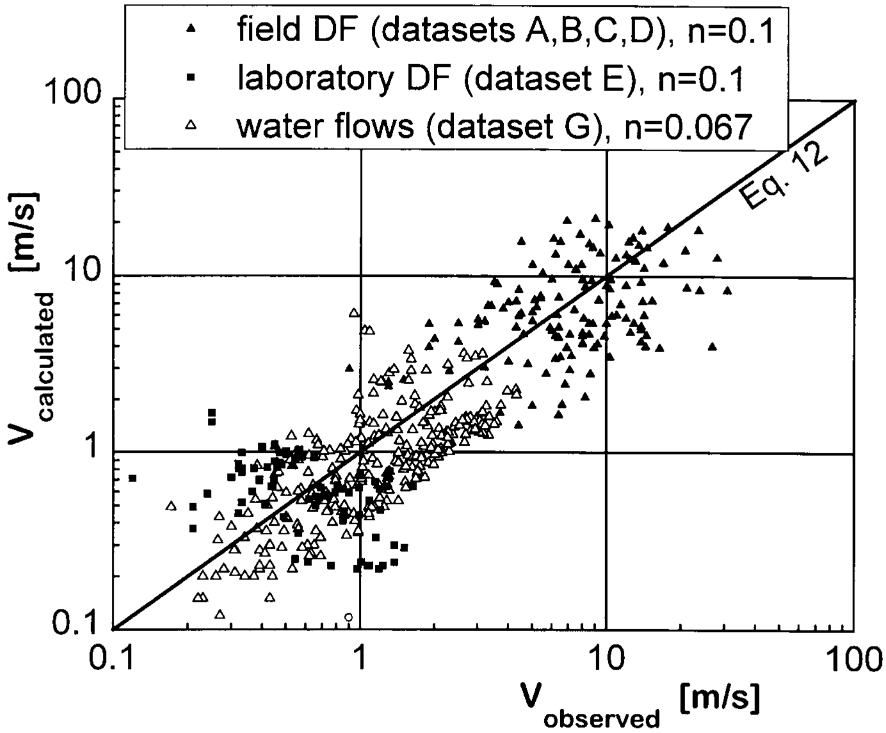

Figure 5a. Comparison of observed mean velocities of debris flows and water flows with those calculated with the Manning–Strickler Equation (12). The abbriviation DF refers to debris flows.

Table VII. Correlation coefficient r^2 and standard error s_e determined between calculated and measured flow velocities in the logarithmic domain. 'na' indicates not applicable

Data set	Application of Equation	Manning's n	r^2	s_e
Debris flows				
A, B, C, D, E	(19)	0.1	0.69	0.31
A, B, C, D	(19)	0.1	0.18	0.24
A	(19)	0.1	0.76	0.084
A, B, C, D	(21)	na	0.71	0.17
A	(21)	na	0.70	0.11
Water flows				
G	(19)	0.067	0.53	0.22
F, G	(21)	na	0.70	0.12

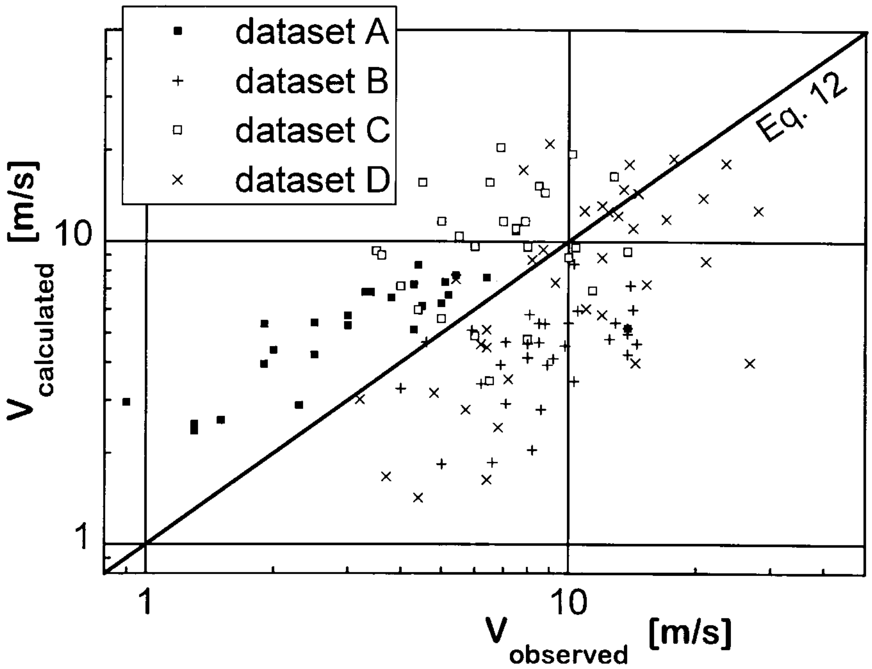

Figure 5b. Comparison of observed mean velocities of different datasets of field debris flows with those calculated with the Manning–Strickler Equation (12).

It is interesting to note that the mean velocity of debris flows and clear water flows can be described in a first approximation with almost the same formulae. In a laboratory study of a steep channel it has been found that for a given discharge and slope, the mean flow velocity differs very little for either clear water flows over a fixed rough bed or for intense sediment transport flows with the same bed material; this has lead to the hypothesis that the flow velocity could be a controlling parameter governing water-driven flows in steep environments (Rickenmann, 1991).

3.4. TRAVEL DISTANCE

The total travel distance, L, of a debris flow may be important to know for a rough delineation of potentially endangered areas. It has been found for rockfalls or sturzstroms that the mean gradient of the flow path H_e/L depends to some extent on the volume of the rockfall (Scheidegger, 1973; Iverson, 1997). Here H_e is the elevation difference between the starting point and the lowest point of deposition of the mass movement. Similarly, it can be shown for debris flows that a dependence of L on H_e and M exists (Figure 7). The data used in Figure 7 are listed in Table VIII. The product of M and H_e can be considered as energy potential of the mass movement.

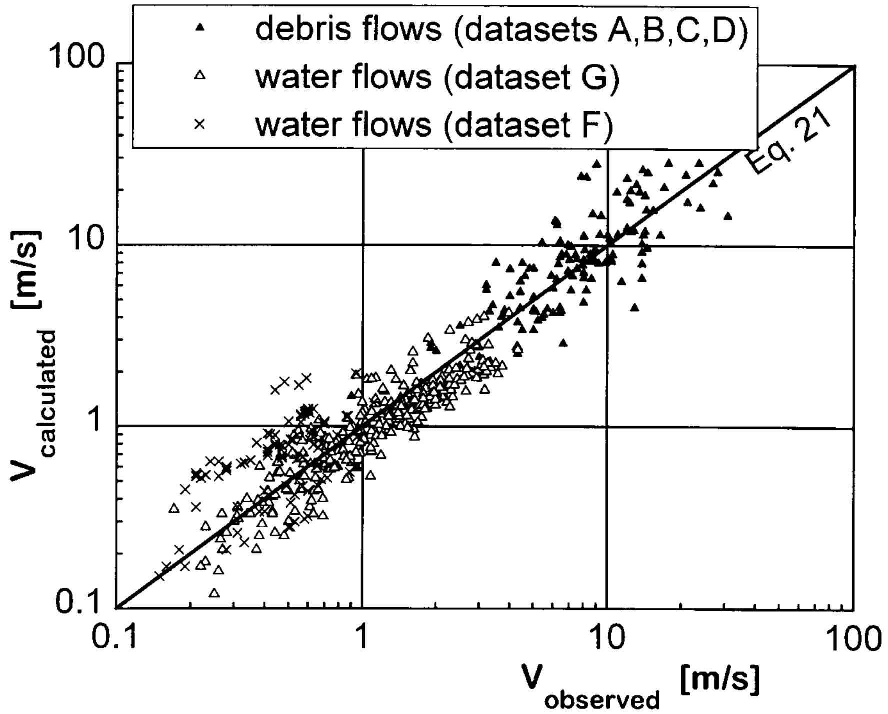

Figure 6. Comparison of observed mean velocities of debris flows and water flows with those calculated as a function of peak discharge and slope (Equation (21)).

The relationship satisfying Froude (or geometric) scaling can be given as follows (Equation (A18b) in the Appendix):

$$L_* = 30(MH_e)_*^{1/4}, \tag{22}$$

where the constant $A_6 = 30$ has been selected to approximate average L values for the debris flow field data.

It is observed that rockfalls/sturzstroms have comparatively smaller travel distances than the debris flows which may possibly be explained with smaller water contents in the flowing masses. The Mount St. Helens lahars and the Nevado del Ruiz mudflow, on the other hand, have comparatively high L values; they possibly involved larger water contents in the flowing mixtures than the majority of the debris flow data in Figure 7 which mostly represent alpine type debris flows.

The following regression equation between L, M and H_e has been derived from the debris flow field data:

$$L_* = 1.9M^{0.16}H_e^{0.83}. \tag{23}$$

The comparison of Equation (23) with the data of Table VIII is shown in Figure 8. The rockfall/sturzstrom data seem to follow a similar trend as the debris flow data.

Table VIII. Data on total travel distance, debris-flow volume of mass movements, and the elevation difference of the flow path, used in Figures 7 and 8

Flow type, Country/Region	N	L [m]	M [m^3]	H_e [m]	Source
Swiss Alps, debris flows	140	300–12,640	1,000–100,000	110–1,820	VAW (1992), M. Zimmermann, written comm. (1996)
Canadian Cordillera, debris flows	8	1,250–3,500	1,500–175,000	660–1,470	M. Jakob, written comm. (1995)
Japan (Kamikamihori valley), debris flows	6	62,111–2,545	710–14,800	570–620	Okuda & Suwa (1981), assumed starting point
U.S.A.: Mt. St. Helens, Mt. Rainier; Columbia: Nevado del Ruiz, Iahars	3	18,500–90,000	4,000,000–8,000,000	900–5,000	Pierson (1985), Pierson et al. (1990), Pierson (1995), Schilling & Iverson (1997)
Rockfalls/Sturzstroms	51	500–18,900	150,000–20,000 Mio.	390–2400	Hsü (1975), Abele (1974), Li (1983)
USGS flume, debris flows	13	88–112	6.2–13	41	Major (1997)
Overall	*232*	*88–90,000*	*6.2–20,000 Mio.*	*41–5,000*	

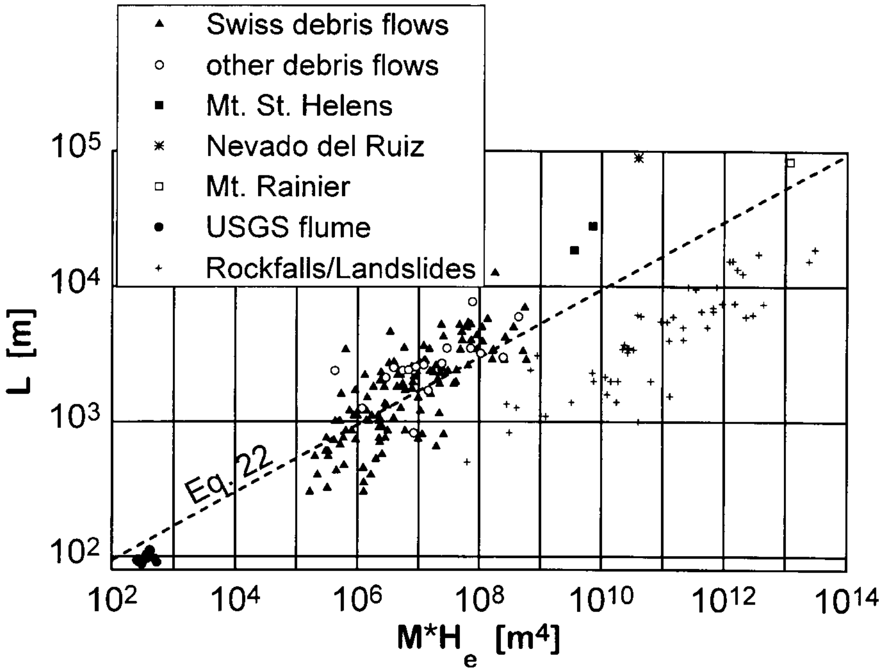

Figure 7. Total travel distance (L) of mass movements in relation to an expression for the energy potential, the product of material volume (M) and elevation difference (H_e). Also shown is the semi-theoretical relationship satisfying Froude or geometric similarity (Equation (22)).

It is noted that H_e is not known a priori. When applying Equation (23) for predictive purposes, a relation between L and H_e describing the longitudinal profile of the expected flow path also has to be defined. For a given estimate of M, a solution for L can then be determined either graphically or mathematically. H_e in combination with L is a measure of the mean slope of the potential flow path. As the longitudinal profile can be assumed a priori, inclusion of H_e improves the prediction of L. A similar procedure has been proposed by Schilling and Iverson (1997) for lahars.

3.5. RUNOUT DISTANCE ON FAN

For a more detailed delineation of potentially endangered areas, the runout distance on the fan, L_f, of a debris flow should be known. L_f is defined as the distance from the fan apex to the lowest point of debris deposits, and it is assumed that for the data in Table IX deposition generally occurred outside the channel downstream of the fan apex. From geometric considerations it can be expected that L_f depends to some extent on the debris-flow volume which is supported by the data of Table IX

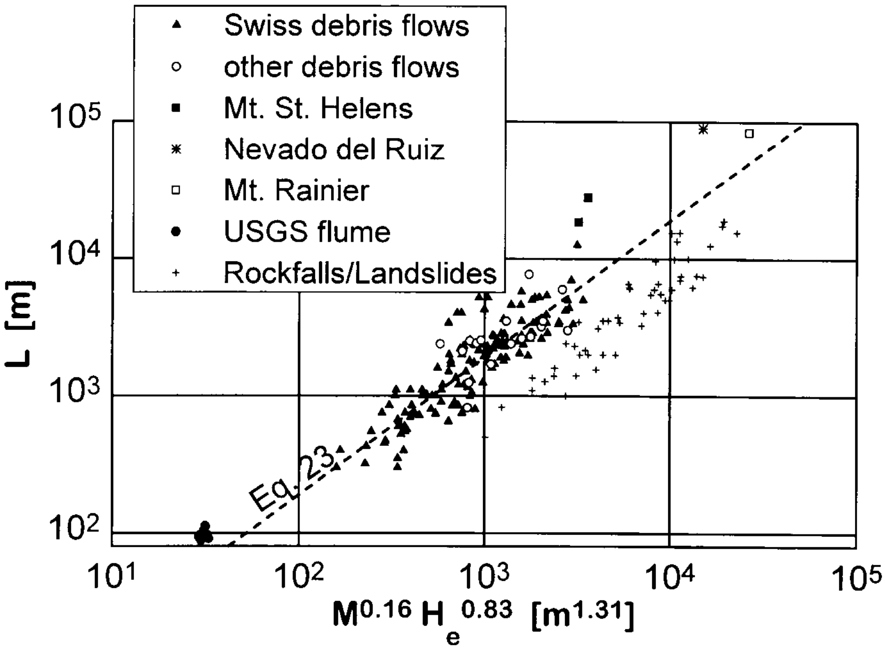

Figure 8. Total travel distance (L) of mass movements in relation to an expression obtained from a regression calculation using debris flow field data only. Also shown is the line of the regression Equation (23).

in Figure 9. The relationship satisfying Froude (or geometric) scaling can be given as follows (Equation (A20b) in the Appendix):

$$L_{f*} = 15 M_*^{1/3}, \tag{24}$$

where the constant A_7 = 15 has been selected to approximate average L_f values for the debris flow field data.

It is found that the scatter of the debris flow field data is in a similar range if L_f is plotted as a function of the product of M and H_e. For a better prediction of L_f than by Equation (24), no other empirical equation of the type of Equation (23) could be found for the data of Table IX. It is assumed that changes in the channel geometry on the fan and different material properties are relatively more important in assessing the runout distance L_f, than are corresponding properties along the whole flow path in assessing the total travel distance L. Equation (24) is not recommended for practical application as the scatter between predicted and observed values is too large.

4. Summary and Conclusions

With respect to the hazard assessment of torrent catchments, it is important to determine whether debris flows are likely to occur or not. The basic requirements

Table IX. Data on runout distance, event volume of mass movements, and the elevation difference of the flow path, used in Figure 9

Flow type, Country/Region	N	L_f [m]	M [m^3]	H_e [m]	Source
Swiss Alps, debris flows	140	71–1,300	1,000–215,000	110–1,820	VAW (1992); M. Zimmermann, written comm. (1996)
Canada, Austria, Japan (Kamikamihori); debris flows	13	21–2,000	700–400,000	570–1,100	Aulitzky (1970); Okuda & Suwa (1981); Fannin & Rollerson (1993)
Columbia: Nevado del Ruiz; lahars	1	16,000	8,000,000	5,000	Pierson *et al*. (1990)
Landslides/Rockfalls	27	300–12,700	150,000–12,000 Mio.	260–2250	Hsü (1975); Abele (1974); Li (1983)
USGS flume, debris flows	13	6.3–30.3	6.2–13	41	Major (1997)
Laboratory debris flows	42	0.3–2.3	0.0026–0.026	0.41–0.59	Liu (1995)
Overall	*236*	*0.3–16,000*	*0.0026–12,000 Mio.*	*0.41–5,000*	

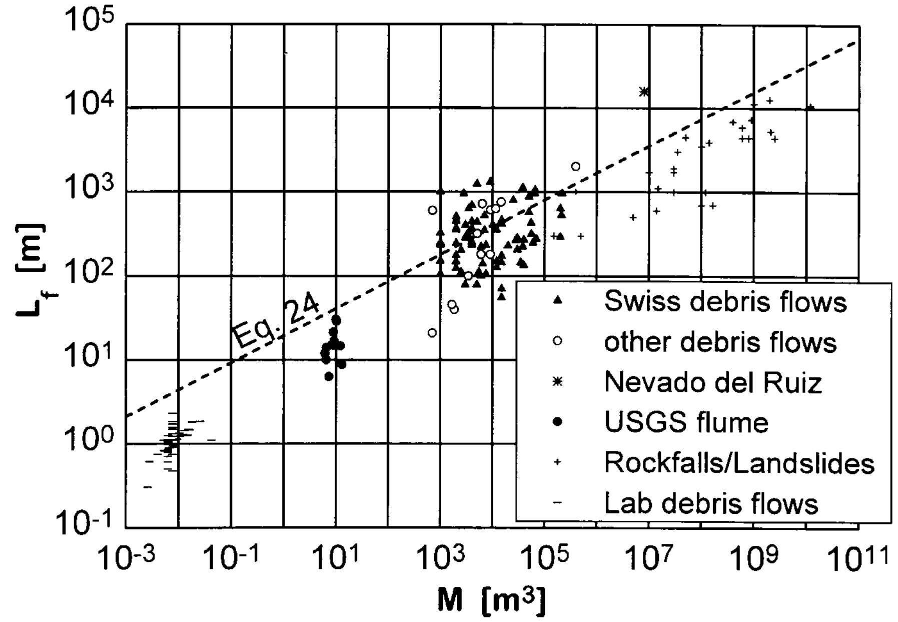

Figure 9. Runout distance (L_f) of mass movements on the fan in relation to the corresponding material volume (M). Also shown is the semi-theoretical relationship satisfying Froude or geometric similarity (Equation (24)).

for the occurrence of debris flows are steep slopes, sufficient volumes of debris material relatively easy to mobilize, and sufficient water to trigger the flow. Further characteristics observed in the field may also be used to estimate a relative probability of debris-flow occurrence (Aulitzky, 1980; Rickenmann, 1995).

Many empirical formulae have been proposed to estimate the debris mass likely to be eroded, based on morphometric parameters of a torrent catchment. Such relationships can probably be improved if lithologic parameters and factors controlling sediment supply are also taken into account. At present it is recommended that a geomorphologic assessment in the field of the material likely to be mobilized may be the best approach if one intends to arrive at a more precise estimate of a possible debris-flow volume. Once a design debris-flow volume has been determined, a number of other important parameters characterizing debris-flow behavior can be estimated according to the procedure illustrated in Figure 1.

It has been shown in several studies that the peak discharge of a debris flow surge can be related to the debris-flow volume. The power law empirical relationship describing the data from debris flows of different magnitude is in agreement with a semi-theoretical relationship having approximately the same exponent (Figure 2). The semi-theoretical relationship has been derived under the assumption that Froude scaling is applicable to the mean flow behavior of debris flows. It is interesting to observe that the intercept of the empirical relationship appears to depend on the material composition of the debris mixture (Figure 3).

The flow resistance of debris flow surges may be estimated with similar formulae as used for clear water flows (Figures 5 and 6). When applying the Newtonian laminar or the dilatant inertial grain shearing approach to the empirical data on the mean velocity of debris flows, the scatter about the semi-theoretical scaling relationship is much larger (Figure 4(a)). Numerical simulations of unsteady debris flows in torrent channels also support the better performance of flow resistance equations similar to those used for turbulent clear water flows. The application of a Manning–Strickler type equation to debris flows indicates that the *n* value might depend to some extent on the material composition of the mixture. If the peak discharge is known, the mean velocity may alternatively be estimated as a function of the discharge and the bedslope.

The total travel distance of debris flows can be described as a function of the debris-flow volume and the elevation difference between the highest and lowest point of the flow path. Since the second parameter is not known a priori, information on the longitudinal profile of the expected flow path must be used in addition in order to make a rough estimate of the travel distance for a given debris-flow volume.

The runout distance on the fan shows some dependence on the debris-flow volume. However, the scatter between predicted and observed values is more than order of magnitude. For a practical assessment of potentially affected zones, it is recommended to use other methods additionally. For example, one could infer possible deposition patterns from debris flow events in the past, which occurred in the same or in other torrents, or one may use a numerical simulation model.

Due to the complexity of the debris flow process, the field data applied to the simple empirical relationships presented in this paper show a considerable scatter. It should be pointed out that most of these relationships can only give an order of magnitude estimate of some debris flow parameters, but that they cannot provide an accurate prediction of these values. More research is needed to quantify for example the influence of material characteristics and solid concentration on debris flow behavior.

Acknowledgements

I would like to thank Matthias Jakob, Hiroshi Suwa, Zhaoyin Wang, and Markus Zimmermann for providing me with data on debris flow parameters. I am grateful to Gian Reto Bezzola, Tim Davies, Christoph Hegg, Thilo Koch, Dani Weber, and Markus Zimmermann for commenting on an earlier draft of the manuscript and to anonymous reviewers for their suggestions for improvements.

Appendix: Derivation of Scaling Equations

For the derivation of the scaling equations it is assumed that Froude similarity must be satisfied for the flow process of debris flows. Froude similarity is considered a necessary requirement since debris flows are a gravitational process with a fluid-like flow behavior and having a free surface. The index $_*$ is used here to denote the ratio of two variables of the same kind but of different magnitude, e.g., $\lambda_* = \lambda_1/\lambda_2$, where the indices 1 and 2 refer for example to prototype and laboratory flows and λ is a characteristic length scale. For Froude scaling (e.g., Henderson 1966) we have to satisfy the relationships:

$$Q_* = Q_{p2}/Q_{p1} \sim \lambda_*^{5/2}, \quad \text{(A1)}$$

$$M_* = M_2/M_1 \sim \lambda_*^3. \quad \text{(A2)}$$

Combining (A1) and (A2) we obtain a theoretical relationship between peak discharge Q_p and debris-flow volume M for debris flows of different size:

$$Q_* \sim (M_*^{1/3})^{5/2} \sim M_*^{5/6} \quad \text{(A3a)}$$

or

$$Q_* = A_1 M_*^{5/6}, \quad \text{(A3b)}$$

where A_1 is an empirical constant.

Considering similar relationships between other parameters, we can base the analysis on the respective Froude scaling relationships for the dimensions of time [s], length [m], and mass [kg] involved in the parameters of interest. For these dimensions we have to satisfy the relationships:

$$[\mathrm{s}] \sim \lambda_*^{1/2}, \quad \text{(A4)}$$

$$[\mathrm{m}] \sim \lambda_*^1, \quad \text{(A5)}$$

$$[\mathrm{kg}] \sim \rho_* \lambda_*^3 = \lambda_*^3, \quad \text{(A6)}$$

where ρ is the density of the fluid or solids, and $\rho_* = 1$ is assumed.

Considering Newtonian laminar flow, and postulating that Reynold's similarity should be satisfied beside Froude similarity, we find for the scaling of the dynamic viscosity:

$$\mu_* \sim [\mathrm{kg/s\ m}] \sim \lambda_*^3/(\lambda_*^{1/2}\lambda_*^1) = \lambda_*^{3/2}. \quad \text{(A7)}$$

Combining (A7) and (A1) we can write

$$\mu_* \sim (Q_*^{2/5})^{3/2} = Q_*^{3/5} \quad \text{(A8a)}$$

or

$$\mu_* = A_2 Q_*^{3/5}, \quad \text{(A8b)}$$

where A_2 is an empirical constant.

Considering dilatant inertial flow, and postulating that Froude similarity should be satisfied beside keeping the Bagnold's number (e.g., Takahashi 1991) constant, we can find for the scaling of the parameter ξ

$$\xi_* \sim 1/[\mathrm{s\ m}^{1/2}] \sim 1/(\lambda_*^{1/2}\lambda_*^{1/2}) = \lambda_*^{-1}. \tag{A9}$$

Combining (A9) and (A1) we can write

$$\xi_* \sim 1/(Q_*^{2/5})^1 = Q_*^{-2/5} \tag{A10a}$$

or

$$\xi_* = A_3 Q_*^{-2/5}. \tag{A10b}$$

where A_3 is an empirical constant.

For Manning's n we have

$$n_* \sim [\mathrm{s}]/[\mathrm{m}^{1/3}] \sim \lambda_*^{1/2}/\lambda_*^{1/3} = \lambda_*^{1/6}. \tag{A11}$$

Combining (A11) and (A1) we can write

$$n_* \sim (Q_*^{2/5})^{1/6} \sim Q_*^{1/15} \tag{A12a}$$

or

$$n_* = A_4 Q_*^{1/15}, \tag{A12b}$$

where A_4 is an empirical constant.

For Chezy C we have

$$C_* \sim [\mathrm{m}^{1/2}]/[\mathrm{s}] \sim \lambda_*^{1/2}/\lambda_*^{1/2} = 1 \tag{A13a}$$

or

$$C_* = \mathrm{const.} \tag{A13b}$$

From (A13) we conclude that the flow resistance parameter C_* should show no dependence on Q_* for debris flows having the same material properties.

Considering the mean velocity Equation (14), and postulating that Froude similarity should be satisfied, we can find for the scaling of the flow resistance parameter C_1:

$$C_{1*} \sim [\mathrm{m}^{0.7}/\mathrm{s}] \sim (\lambda_*^{0.7}/\lambda_*^{0.5}) = \lambda_*^{0.2}. \tag{A14}$$

Combining (A14) and (A1) we can write

$$C_{1*} \sim (Q_*^{2/5})^{1/5} = Q_*^{2/25} \tag{A15a}$$

or

$$C_{1*} = A_5 Q_*^{2/25}, \tag{A15b}$$

where A_5 is an empirical constant.

For the total travel distance L we can write

$$L_* \sim \lambda_*, \tag{A16}$$

$$(MH)_* \sim \lambda_*^3 \lambda_* = \lambda_*^4. \tag{A17}$$

Combining (A16) and (A17) we obtain a theoretical relationship between travel distance L and the energy potential (MH) for debris flows of different size:

$$L_* \sim (MH)_*^{1/4}, \tag{A18a}$$

or

$$L_* = A_6 (MH)_*^{1/4}, \tag{A18b}$$

where A_6 is an empirical constant.

For the runout distance L_f on the fan we can write

$$L_{f*} \sim \lambda_*, \tag{A19}$$

$$M_* \sim \lambda_*^3. \tag{A2}$$

Combining (A19) and (A2) we obtain a theoretical relationship runout distance and the debris-flow volume for debris flows of different size:

$$L_{f*} \sim M_*^{1/3} \tag{A20a}$$

or

$$L_{f*} = A_7 M_*^{1/3}, \tag{A20b}$$

where A_7 is an empirical constant.

References

Abele, G.: 1974, Bergstürze in den Alpen: Ihre Verbreitung, Morphologie und Folgeerscheinungen [rockfalls in the Alps: distribution, morphology, and impacts], *Wissenschaftliche Alpenvereinshefte* 25, München (in German).

Arattano, M., Mortara, G., Deganutti, A. M., and Marchi, L.: 1996, Esperienze di monitoraggio delle colate detriche nel torrente Moscardo (Alpi Carniche) [experience from debris flow monitoring in the Moscardo torrent], *Geoingeneria Ambientale e Mineraria*, no. 2–3, Supplemento: Quaderni di Studi no. 20: Studi sui Debris Flow, pp. 33–43 (in Italian).

Aulitzky, H.: 1970, Der Enterbach am 26. Juli 1969. Versuch der Analyse eines Murganges als Grundlage fuer die Neuerstellung einer zerstoerten Wildbachverbauung [the Enterbach on 26 July 1969. Attempt at analysing a debris flow as a basis for the reconstruction of destroyed control works], *Wildbach- und Lawinenverbau* **34**(1), 31–66 (in German).

Aulitzky, H.: 1973, Berücksichtigung der Wildbach- und Lawinengefahrengebiete als Grundlage der Raumordnung von Gebirgsländern [torrent and avalanche risk assessment as basis for land development in mountainous countries], *100 Jahre Hochschule für Bodenkultur*, Band IV, Teil 2, pp. 81–117 (in German).

Aulitzky, H.: 1980, Preliminary two-fold classification of torrents, *Proc. Int. Symp. Interpraevent*, Bad Ischl, Austria, Bd. 4, pp. 285–310.

Aulitzky, H.: 1984, Vorlaeufige, zweigeteilte Wildbachklassifikation [preliminary two-fold classification of torrents], *Wildbach- und Lawinenverbau* **48** (Sonderheft Juni 1984), 7–60 (in German).

Bathurst, J. C.: 1985, Flow resistance estimation in mountain rivers, *J. Hydr. Engng, ASCE* **111**(4), 625–643.

Costa, J. E.: 1984, Physical geomorphology of debris flows, In: J. E. Costa and P. J. Fleischer (eds), *Developments and Applications of Geomorphology*, Springer, Berlin, Germany, pp. 268–317.

Costa, J. E.: 1988a, Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, In: V. R. Baker *et al.* (eds), *Flood Geomorphology*, John Wiley & Sons, New York, pp. 113–122.

Costa, J. E.: 1988b, Floods from dam failures, In: V. R. Baker *et al.* (eds), *Flood Geomorphology*, John Wiley & Sons, New York, pp. 439–463.

D'Agostino, V.: 1996, Analisi quantitativa e qualitativa del trasporto solido torrentizio nei bacini montani de Trentino Orientale [quantitative and qualitative analysis of sediment transport in torrents of mountainous catchments of eastern Trentino], *Scritti dedicati a Giovanni Tournon*, Associazione Idrotecnica Italiana, Sezione Liguria Piemonte e Valle d'Aosta (in Italian).

Davies, T. R. H.: 1990, Debris flow surges – experimental simulation, *J. Hydrology (N.Z.)* **29**(1), 18–46.

Davies, T. R. H.: 1994, Dynamically similar small-scale debris flow models, *Proc. Int. Workshop on Floods and Innundations Related to Large Earth Movements*, Trento, Italy, IAHR, pp. A12.1–A12.11.

Davies, T. R. H.: 1997, Using hydroscience and hydrotechnical engineering to reduce debris flow hazards, *Proc. First Int. Conf. on Debris Flow Hazards Mitigation*, San Francisco, U.S.A., ASCE, pp. 787–810.

Fannin, R. J. and Rollerson, T. P.: 1993, Debris flows: some physical characteristics and behaviour, *Can. Geotech. J.* **30**, 71–81.

Gallino, G. L. and Pierson, T. C.: 1985, Polallie Creek debris flow and subsequent dam-break flood of 1980, East Fork Hood River Basin, Oregon, U.S. Geological Survey Water-Supply Paper.

Garcia Aragon, J. A.: 1996, A hydraulic shear stress model for rapid, highly concentrated flow, *J. Hydr. Res.* **34**(5), 589–596.

Griffiths, G. A.: 1981, Flow resistance in coarse gravel bed rivers, *J. Hydr. Div., ASCE* **107**(7), 899–918.

Haeberli, W.: 1983, Frequency and characteristics of glacier floods in the Swiss Alps, *Ann. Glaciology* **4**, 85–90.

Hampel, R.: 1977, Geschiebewirtschaft in Wildbächen [sediment budget of torrents], *Wildbach- und Lawinenverbau* **41**(1), 3–34 (in German).

Han, G. and Wang, D.: 1996, Numerical modeling of Anhui debris flow, *J. Hydr. Engng, ASCE* **122**(5), 262–265.

Harris, S. A. and Gustafson, C. A.: 1993, Debris flow characteristics in an area of continuous permafrost, St. Elias Range, Yukon Territory, *Z. Geomorph. N.F.* **37**(1), 41–56.

Henderson, F. M.: 1966, *Open Channel Flow*, MacMillan, New York.

Hodel, H.: 1993, Untersuchung zur Geomorphologie, der Rauheit des Strömungswiderstandes und des Fliessvorganges in Bergbächen [study on the geomorphology, the roughness of the flow resistance, and the flow process in mountain streams], *Diss. ETH Nr. 9830*, ETH Zürich (in German).

Hsü, K. J.: 1975, Catastrophic debris streams (sturzstroms) generated by rockfalls, *Geol. Soc. Am. Bull.* **86**, 129–140.

Hungr, O., Morgan, G. C., and Kellerhals, R.: 1984, Quantitative analysis of debris torrent hazards for design of remedial measures, *Can. Geotechnical J.* **21**, 663–677.

Hungr, O.: 1995, A model for the runout analysis of rapid flow slides, *Can. Geotechnical J.* **32**, 610–623.

Ikeya, H.: 1989, Debris flow and its countermeasures in Japan, *Bull. Int. Ass. Engng Geol.* **40**, 15–33.

Iverson, R. M. and LaHusen, R. G.: 1993, Friction in debris flows: inferences from large-scale flume experiments, In: H. W. Shen *et al.* (eds), *Hydraulic Engineering '93*, ASCE, Vol. 2, pp. 1604–1609.

Iverson, R. M.: 1997, The physics of debris flows, *Rev. Geophysics* **35**(3), 245–296.

Jarrett, R. D.: 1984, Hydraulics of high-gradient streams, *J. Hydr. Engng, ASCE* **110**(11), 1519–1539.

Jitousono, T., Shimokawa, E., and Tsuchiya, S.: 1996, Debris flow following the 1994 eruption with pyroclastic flows in Merapi volcano, Indonesia, *J. Jap. Soc. Erosion Control Engng* **48**(Special Issue), 109–116.

Johnson, A. M.: 1984, Debris Flow, In: D. Brunsden and D. B. Prior (eds), *Slope Instability*, John Wiley and Sons, New York, pp. 257–361.

Keremculov, V. A. and Zuckerman, I. G.: 1983, Sill-flows and transportation of sediments in the channels of steep slope. Modelling of sillflows, *Proc. IAHR Congress*, Moscow, pp. 325–328.

Koch, T.: 1998, Testing of various constitutive equations for debris flow modelling, In: K. Kovar *et al.* (eds), *Hydrology, Water Resources and Ecology in Headwaters*, IAHS Publ. No. 248, Merano, Italy, pp. 249–257.

Kronfellner-Kraus, G.: 1984, Extreme Feststofffrachten und Grabenbildungen von Wildbächen [extreme sediment loads and erosion of torrents], *Proc. Int. Symp. Interpraevent*, Villach, Austria, Bd. 2, pp. 109–118 (in German).

Kronfellner-Kraus, G.: 1987, Zur Anwendung der Schätzformel fuer extreme Wildbach-Feststofffrachten im Süden und Osten Oesterreichs [on the application of the formula to estimate extreme sediment loads in torrents of southern and eastern Austria], *Wildbach- und Lawinenverbau* **51**(106), 187–200 (in German).

Li, T.: 1983, A mathematical model for predicting the extent of a major rockfall, *Z. Geomorph. N.F.* **27**(4), 437–482.

Liu, X.: 1995, Model experiments on risk range of debris flow fan, *Proc. XX IUFRO Congress*, Finland, Techn. Session on Natural Disasters in Mountainous Areas, pp. 27–37.

Major, J. J. and Pierson, T. C.: 1992, Debris flow rheology: experimental analysis of fine-grained slurries, *Wat. Resour. Res.* **28**(3), 841–857.

Major, J. J.: 1997, Depositional processes in large-scale debris flow experiments, *J. Geol.* **105**, 345–366.

Marchi, L. and Tecca, P. R.: 1996, Magnitudo delle colate detriche nelle Alpi Orientali Italiane [magnitude of debris flows in the eastern Italian Alps], *Geoingeneria Ambientale e Mineraria*, no. 2–3, pp. 79–86 (in Italian).

Mizuyama, T., Kobashi, S., and Ou, G.: 1992, Prediction of debris flow peak discharge, *Proc. Int. Symp. Interpraevent*, Bern, Switzerland, Bd. 4, pp. 99–108.

Nakamura, J.: 1980, Investigation manual on prediction of occurrence of Dosekiryu [debris flows], delineation of dangerous zone affected by Dosekiryu and arrangement of warning and evacuation system in mountain torrents in Japan, *Proc. Int. Symp. Interpraevent*, Bad Ischl, Austria, Bd. 3, pp. 41–81.

Okuda, S. and Suwa, H.: 1981, Some relationships between debris flow motion and micro-topography for the Kamikamihori Fan, North Japan Alps, In: T. P. Burt and D. E. Walling (eds), *Catchment Experiments in Fluvial Geomorphology*, pp. 447–464.

Pierson, T. C.: 1980, Erosion and deposition by debris flows at Mt. Thomas, North Canterbury, New Zealand, *Earth Surf. Proc. and Landf.* **5**, 227–247.

Pierson, T. C.: 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington, *Geol. Soc. Am. Bul.* **96**, 1056–1069.

Pierson, T. C.: 1986, Flow behavior of channelized debris flows, Mt. St. Helens, Washington, In: A. D. Abraham (ed), *Hillslope Processes*, Allen & Unwin, Boston, pp. 269–296.

Pierson, T. C., Janda, R. J., Thouret, J. C., and Borrero, C. A.: 1990, Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Columbia, and consequent mobilization, flow and deposition of lahars, *J. Volcanology Geothermal Res.* **41**, 17–66.

Pierson, T. C.: 1995, Flow characteristics of large eruption-triggered debris flows at snow-clad volcanoes: constraints for debris-flow models, *J. Volcanology Geothermal Res.* **66**, 283–294.

PWRI: 1988, Technical standard for measures against debris flow (draft), Technical Memorandum of PWRI, No. 2632, Ministry of Construction, Japan.

Rickenmann, D.: 1990, Debris flows 1987 in Switzerland: Modelling and sediment transport, In: R. O. Sinniger and M. Monbaron (eds), *Hydrology in Mountainous Regions II*, IAHS Publ. No. 194, pp. 371–378.

Rickenmann, D.: 1991, Hyperconcentrated flow and sediment transport at steep slopes, *J. Hydr. Engng, ASCE* **117**(11), 1419–1439.

Rickenmann, D. and Zimmermann, M.: 1993, The 1987 debris flows in Switzerland: documentation and analysis, *Geomorphology* **8**, 175–189.

Rickenmann, D.: 1994, An alternative equation for the mean velocity in gravel-bed rivers and mountain torrents, *Proc. 1994 Nat. Conf. on Hydraulic Engineering*, Buffalo N.Y., U.S.A., ASCE, Vol. 1, pp. 672–676.

Rickenmann, D.: 1995, Beurteilung von Murgängen [Assessment of debris flows], *Schweizer Ingenieur und Architekt* (48), 1104–1108 (in German).

Rickenmann, D.: 1996, Fliessgeschwindigkeit in Wildbächen und Gebirgsflüssen [Flow velocity in torrents and mountainous streams], *Wasser, Energie, Luft* **88**(11/12), 298–304 (in German).

Rickenmann, D. and Koch, T.: 1997, Comparison of debris flow modelling approaches, *Proc. First Int. Conf. on Debris Flow Hazards Mitigation*, San Francisco, U.S.A., ASCE, pp. 576–585.

Rickenmann, D.: 1998, Antwort zu Diskussion von 'Fliessgeschwindigkeit in Wildbächen und Gebirgsflüssen' [Reply to discussion of 'Flow velocity in torrents and mountainous streams' by D. Rickenmann], *Wasser, Energie, Luft* **90**(5/6), 133–134 (in German).

Ruf, G.: 1990, Fliessgeschwindigkeiten in der Ruetz/Stubaital/Tirol [Flow velocities in the Ruetz/Stubai valley/Tyrol], *Wildbach- und Lawinenverbau* **54**(115), 219–227 (in German).

Rutherford, I. D., Bishop, P., and Loffler, T.: 1994, Debris flows in northeastern Victoria, Australia: occurrence and effects on the fluvial system, In: *Variability in Stream Erosion and Sediment Transport*, IAHS Publ. No. 224, pp. 359–369.

Scheidegger, A. E.: 1973, On the prediction of the reach and velocity of catastrophic landslides, *Rock Mechanics* **5**, 231–236.

Schilling, S. P. and Iverson, R. M.: 1997, Automated, reproducable delineation of zones at risk from inundation by large volcanic debris flows, *Proc. First Int. Conf. on Debris Flow Hazards Mitigation*, San Francisco, U.S.A., ASCE, pp. 176–186.

Suwa, H., Okunishi, K., and Sakai, M.: 1993, Motion, debris size and scale of debris flows in a valley on Mount Yakedake, Japan, *Proc. of Sediment Problems: Strategies for Monitoring, Prediction and Control*, Yokohama, IAHS Publ. No. 217, pp. 239–247.

Takahashi, T.: 1991, Debris Flow, *IAHR Monograph Series*, Balkema Publishers, The Netherlands.

Takahashi, T., Sawada, T., Suwa, H., Mizuyama, T., Mizuhara, K., Wu, J., Tang, B., Kang, Z., and Zhou, B: 1994, Japan-China joint research on the prevention from debris flow hazards, Research Report, Japanese Ministry of Education, Science and Culture, Int. Scientific Research Program No. 03044085.

Takei, A.: 1980, Interdependence of sediment budget between individual torrents and a river-system, *Proc. Int. Symp. Interpraevent*, Villach, Austria, Bd. 2, pp. 35–48.

Thompson, S. M. and Campbell, P. L.: 1979, Hydraulics of a large channel paved with boulders, *J. Hydr. Res.* **17**(4), 341–354.

Thorne, C. R. and Zevenbergen, L. W.: 1985, Estimating mean velocity in mountain rivers, *J. Hydr. Engng, ASCE* **111**(4), 612–624.

VanDine, D. F.: 1985, Debris flows and debris torrents in the Southern Canadian Cordillera, *Can. Geotech. J.* **22**, 44–68.

VAW: 1992, Murgänge 1987: Dokumentation und Analyse [Debris flows 1987: documentation and analysis], Unpublished Report, No. 97.6, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie (VAW), ETH Zürich (in German).

Walder, J. S. and O'Connor, J. E.: 1997, Methods for predicting peak discharge of floods caused by failure of natural and constructed earthen dams, *Water Resour. Res.* **33**(10), 2337–2348.

Wang, Z. and Zhang, X.: 1990, Initiation and laws of motion of debris flow, *Proc. Hydraulics/Hydrology of Arid Lands*, ASCE, pp. 596–691.

Watanabe, M. and Ikeya, H.: 1981, Investigation and analysis of volcanic mud flow on Mt. Sakurajima, Japan, *Proc. Symp. on Erosion and Sediment Transport Measurement*, Florence, Italy, IAHS Publ. No. 133, pp. 245–256.

Webb, R. H., Pringle, P. T., Reneau, S. L., and Rink, G. R.: 1988, Monument Creek debris flow, 1984: implications for formation of rapids on the Colorado River in Grand Canyon National Park, *Geology* **16**, 50–54.

Zeller, J.: 1985, Feststoffmessung in kleinen Gebirgseinzugsgebieten [Sediment measurement in small mountainous catchments], *Wasser, Energie, Luft* **77**(7/8), 246–251 (in German).

Zimmermann, M., Mani, P., Gamma, P., Gsteiger, P., Heiniger, O., and Hunziker, G.: 1997a, Murganggefahr und Klimaänderung – ein GIS-basierter Ansatz [Debris flow risk and climatic change – a GIS-based approach], Schlussbericht NFP 31, vdf-ETH Zürich, Switzerland (in German).

Zimmermann, M., Mani, P., and Romang, H.: 1997b, Magnitude-frequency aspects of Alpine debris flows, *Eclogae Geologicae Helvetiae* **90**(3), 415–320.