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How high are bed-moving flows in New Zealand rivers?

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Abstract

This paper documents an attempt to calculate the bed-moving flow in 40 New Zealand river reaches and relate the results to commonly used flow statistics such as the median flow, the mean flow and the mean annual maximum flow. The bed-moving flow is defined here as the flow that is able to initiate movement of bed particles of a designated percentile diameter. Bed-moving flows (Q_B) were calculated for the 50th and 84th percentile diameters (d_{50} and d_{84}). The calculations are based on a competence formula for incipient motion of non-uniform bed-sediments derived by Komar (1989) and also used on New Zealand data by Duncan and Biggs (1998), Duncan *et al.* (1999) and Lorang and Hauer (2003). Grain shear stress was calculated using a field-calibrated relationship presented by Hey (1979). The hydraulic and bed-sediment data used to calculate the bed-moving flows $Q_B(d_{50})$ and $Q_B(d_{84})$ are from Hicks and Mason (1991). The bed-moving flows were calculated successfully for 26 of the 40 river reaches; in the remaining 14 cases the shear stress versus flow relationships did not enable satisfactory solutions to be found. The calculated bed-moving flows were compared to the median flow, the mean flow and the mean annual maximum flow derived from time-series of water level recorded every 15 minutes and converted to flow for a number of years (24 on average for all sites). The strongest correlations for the bed-moving flows $Q_B(d_{50})$ and $Q_B(d_{84})$ were found with the mean annual maximum flow, and the best-fit power curve was nearly linear for both relations. On average, bed-moving flows were 0.18 and 0.38 times the mean annual maximum flow for d_{50} and d_{84}, respectively. However, the variation of individual data points is too large to allow the model to be used for prediction. The results should be regarded as first approximations only, given the uncertainty related to using a competence formula to estimate bed-motion. Improved estimates would require field observations.

Keywords

flood, frequency of flood, bed-substrate, bed stability, incipient motion of bed particles, threshold entrainment, critical shear stress, stream ecology

Introduction

It has been demonstrated that freshes or floods of the order of three to seven times the median flow are able to reduce the biomass

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and diversity of periphyton, especially filamentous green algae (e.g., Biggs and Thomsen, 1995) and macrophytes (Riis and Biggs, 2003). In a study covering many New Zealand rivers, the frequency of flows higher than three times the median flow (*FRE3*) was the flow statistic (out of 32 flow variables) that had the highest correlation coefficients with periphyton data (Clausen and Biggs, 1997). A flow of three times the median flow is a relatively small flood event (and may not even be called a 'flood') in many rivers, and it may not cause much, if any, bed mobility. However, for fine periphyton films and invertebrates, it has been argued that the predominant mechanism of disturbance is the movement of bed sediments (e.g., Scarsbrook and Townsend, 1993). Thus, both the frequency of flows higher than three times the median (*FRE3*) and the frequency of bed-moving flows (FRE_B) seem to have some ecological significance.

A comparison between *FRE3* and FRE_B was made by Duncan and Biggs (1998) for 12 South Island rivers. They found that while some rivers had similar values of both statistics, *FRE3* was higher than FRE_B in most rivers, indicating that three times the median flow is smaller than the bed-moving flow for most sites. This observation generated the following questions: how much higher is the bed-moving flow compared to the median flow, and, is it possible to predict the bed-moving flow from one of the commonly used flow statistics, such as the median flow, the mean flow, or the mean annual maximum flow?

There are examples in the literature of attempts to quantify the bed-moving flow relative to flow statistics. For example, Steeter *et al.* (1994) found that flows of 2–5 times the mean flow were required for initial motion of the bed material in the Colorado River. Andrews (1994) measured sediment transport in a small mountain stream and found that most particles sizes started moving at a flow of approximately 2-3 times the mean flow or approximately half of the bankfull discharge. In another study, Andrews (1984), through computations for 24 gravel-bed rivers, found that the threshold of particle motion was exceeded at flows slightly less than bankfull, but it is not stated how bankfull discharge relates to the mean annual maximum flow. The problem with using bankfull discharge for New Zealand gravel-bed rivers is that often there are no clearly defined banks. Comparison of the results from the various studies reported in the literature is complicated by the fact that often different methods have been used to define and calculate the bed-moving flow.

The aim of this paper is to calculate the bed-moving flow for a wide range of New Zealand rivers, using the formulae of Komar (1989) and Chiew and Parker (1994), as employed by Duncan and Biggs (1998) and Duncan *et al.* (1999), and relate the results to the median flow, the mean flow, and the mean annual maximum flow. The calculations are based on data published by Hicks and Mason (1991).

Theory and methods

Hydraulic resistance to steady flow in natural channels is a combination of skin friction due to the roughness of the bed material (grain roughness) and form resistance caused by bed forms and bends, and drag on granular material in transport above the bed (Hey, 1979; Griffiths, 1989). Thus, the mean shear stress on the bed (τ) can be expressed as the sum of the shear stresses due to grain roughness (τ') and form roughness (τ''):

$$\tau = \tau' + \tau'' \tag{1}$$

Vegetation on the banks and channel bed will also contribute to hydraulic resistance, and we will here consider this as part of the form roughness.

The mean shear stress can be calculated from the hydraulic radius (R) and the friction slope (S_f):

$$\tau = \rho\, g\, R\, S_f \tag{2}$$

where ρ is fluid density and g is gravitational acceleration. As only particle drag contributes to bed transport, incipient motion and sediment transport calculations should not be based on total stress, but on the stress due to grain roughness alone (Einstein, 1942; Meyer-Peter and Muller, 1948; Wilcock and Kenworthy, 2002).

The Shields equation describes the critical grain shear stress (τ'_c) at incipient motion for a bed particle in *uniform* bed substrate (i.e., all particles have the same size and shape) on a horizontal bed:

$$\tau'_c = \tau'^{*}_c\,(\rho_s - \rho)\, g\, d \tag{3}$$

where $\tau'_c{}^*$ is the Shields' parameter or the critical value of the dimensionless shear stress, ρ_s is the substrate density, and d is the diameter of the bed particles. Using compiled flume data, Miller *et al.* (1977) found Shields' parameter to be approximately 0.045 for rough turbulent flow, course grains (d >1 mm) and shallow bed slopes, rather than the 0.06 value originally found by Shields (1936). Yalin and Karahan (1979) also reported an average value of 0.045 for rough turbulent flows.

It is generally accepted that in *non-uniform* bed substrate (with different size particles), larger particles are entrained at lower shear stress than in a bed of uniform (same-size) sediment particles because of increased exposure and instability. The commonly used equation (Shvidchenko *et al.*, 2001) to describe the relative variation of the critical value of the dimensionless bed shear stress (τ'^{*}_{ci}) for a particle with diameter d_i in a non-uniform horizontal bed is:

$$\tau'^{*}_{ci} / \tau'^{*}_{c50} = \text{function}\,(d_i / d_{50}) \tag{4}$$

where τ'^{*}_{c50} is the critical value of the dimensionless shear stress for the particle with the median diameter (d_{50}).

Some observations have suggested that all particle sizes begin moving at approximately the same grain shear stress (near-equal entrainment mobility) (e.g., Wilcock, 1992), while others have shown significantly different degrees of entrainment for different particle sizes (e.g., Komar, 1987, Wathen *et al.*, 1995; Wilcock and McArdell, 1997). A comparison of some of the different versions of equation (4) suggested in the literature show some differences in the critical shear stress, especially for the end size fractions (Shvidchenko *et al.*, 2001). This has been attributed partly to differences in methods of defining the critical shear stress and in particle size distribution, but the differences are not yet completely understood .

The value of τ'^{*}_{c50} has been related to the critical value for the dimensionless shear stress for uniform bed sediment. Values vary between 0.03 and 0.07 (Buffington and Montgomery, 1997). Some of the variation is thought to be due to differences in investigative methods and in other factors such as the shape of the grain size distribution and slope (Buffington and Montgomery, 1997; Shvidchenko, 2001).

In this paper we will use the equation proposed by Komar (1989):

$$\tau'^{*}_{ci} / \tau'^{*}_{c50} = (d_i / d_{50})^{-0.65} \tag{5}$$

This relationship was found by using a value of 0.045 for τ'^{*}_{c50} and reworking data from Milhous (1973), Carling (1983) and Hammond *et al.* (1984) obtained from field studies in which flow velocity and incipient motion of the largest entrained particle were measured concurrently. The equation is applicable for particles with d_i / d_{50} values up to approximately 22 (Komar, 1989). Equation (5) produces values of ($\tau'^{*}_{ci} / \tau'^{*}_{c50}$) in the middle range compared with other versions of equation (4) (Shvidchenko *et al.*, 2001).

Combining equations (3) and (5) and inserting $\tau'^{*}_{c50} = 0.045$, $\rho_s = 2650$ kg/m^3 (representing quartz) and $\rho = 1000$ kg/m^3 (water) give:

$$\tau'_{ci} = 0.045\,(2650\text{-}1000)\; g\; d_{50}^{0.65}\; d_i^{\;0.35} \qquad (6)$$

Equation (6) is valid for horizontal, or near horizontal, beds. When the bed slopes, particles are moved more easily. Based on theoretical considerations and experimental verification, Chiew and Parker (1994) found that the critical grain shear stress at any slope (τ'_{cs}) is reduced by a factor dependant on the bed slope angle (Φ) and the bed material angle of repose (θ):

$$\tau'_{csi} = \tau'_{ci}\cos(\Phi)\;[1 - \tan(\Phi)/\tan(\theta)\;] \quad (7)$$

Most of the sites used in this study (see Data section) have gravel beds ($d_{50} > 8$ mm). We assume that θ is 35°, which is a typical value for gravel (Henderson, 1966, Fig. 10-8). As measurements of bed slope for the sites are not available, we approximate the bed slope angle Φ with the friction slope S_f, such that $\tan(\Phi) = S_f$. The steepest site used in this study has an average S_f of approximately 0.04 (see Data section), which means that the correction for the steepest site is

$$\frac{1}{\sqrt{1+0.04^2}}\left[1-\left(0.04/\tan(35°)\right)\right]=0.942 \;.$$

Thus, in this case the correction for bed slope gives a reduction in critical shear stress of approximately 6%. At most sites the correction for bed slope is less than 2% (see also Results). Although small, we did include the correction in all cases, so that the final equation for calculating the critical value of the grain shear stress is the combination of equations (6) and (7):

$$\tau'_{csi} = 0.045\;1650\,\frac{1-\left(S_f/\tan(35°)\right)}{\sqrt{1+S_f^{\,2}}}\,g\,d_{50}^{\;0.65}\,d_i^{\;0.35} \quad (8)$$

In this study we are interested in determining the critical flow at which most of the bed particles are set in motion, as this will be a significant disturbance with little chance for benthic organisms to find refuge. Incipient motion of d_{84} size particles defines such a situation. However, it can be argued that incipient motion of d_{50} size particles is also an important disturbance. Thus, for comparison, we decided to calculate two bed-moving flows, the flow required to move particles with diameter d_{84}, $Q_B(d_{84})$, and the flow required to move particles with diameter d_{50}, $Q_B(d_{50})$.

By replacing d_i by d_{84} and d_{50} in equation (8) we can calculate the critical grain shear stress associated with $Q_B(d_{84})$ and $Q_B(d_{50})$, respectively. To find the two bed-moving flows we need to establish a relationship between the grain shear stress τ' and the flow Q. Being concerned with the conditions for incipient motion implies that the bed can be considered to be immobile and any form roughness will result from remnant bed forms from previous floods (Griffiths, 1981, 1989). The method we use here to establish a τ' versus Q relationship is to estimate particle drag from equations derived for plane immobile beds. Hey (1979) and Griffiths (1981) provide essentially identical methods for estimating the Darcy-Weisbech friction factor f for a plane, immobile gravel-bed:

$$\frac{1}{\sqrt{f}} = 2.03\;\log\left(\frac{aR}{k_s}\right) \qquad (9)$$

The coefficient a varies with cross-sectional geometry within the limits 11.1 (for an infinitely wide, flat cross-section) to 13.46 (for a semicircular cross-section). An average value of a = 11.75 is used here. The equivalent grain roughness k_s is a function of particle size. A wide range of relationships between k_s and various particle sizes have been presented in hydraulic literature. We have chosen $k_s = 3.5\ d_{84}$ as used by Hey (1979).

As the constants for equation (9) were derived by regression analysis, there will be some variation between the computed and actual friction factor f. Hey (1979) gives a standard error of 12.7% for the variation between calculated and measured f in riffle sections of rivers. At pools, the standard error was 154% due to the development of backwater effects. At most pool sites, where flow is controlled by downstream topography rather than by bed friction, the calculated friction was considerably higher than measured.

Grain shear stress τ' is related to f and mean velocity V by:

$$\tau' = (1/8)\, f \rho\, V^2 \tag{10}$$

By combining equations (9) and (10) and inserting the mentioned values for a and k_s, we obtain:

$$\tau' = \frac{\rho V^2}{8\left[2.03\ \log\left(\dfrac{11.5\, R}{3.5\, d_{84}}\right)\right]^2} \tag{11}$$

From flow gauging results (values of R and V) we can calculate τ' from equation (11) (assuming that we know the value of d_{84}), and by relating this value to the measured Q for a range of flows we can develop a τ' versus Q relationship. This relationship can then be used to find Q_B (the bed-moving flow for the particle size being considered) as the Q value corresponding to the value of τ'_{csi} calculated from equation (8).

At some sites and flows, the calculated grain shear stress τ' exceeds the total shear stress τ calculated from equation (2). Because τ' is calculated using equations derived from regression analysis of river data (Hey, 1979), we might expect τ' to be overestimated by some degree in some situations. Another explanation is that the total shear stress may be limited by backwater effects resulting from a downstream flow constriction. In this situation, the flow can no longer be considered uniform and would be controlled from downstream rather than by the local friction. Where τ' (calculated from equation (11)) exceeds τ (calculated from equation (2)) we assume that the effect of form drag is minimal and that τ' equals τ. Thus, the procedure that was used to calculate Q_B for each site, is:

1) Calculate τ'_{csi} from equation (8)
2) For each flow gauging, calculate τ from equation (2) and τ' from equation (11).
3) For each flow, check that the value of τ' is lower than τ. If τ' is higher than τ, the value of τ' is set equal to the value of τ.
4) Construct a τ' versus Q relationship. The Q value that corresponds to the value of τ'_{csi} is the estimated Q_B.

For most sites, a power function was used to fit the τ' versus Q data, although linear, quadratic, or exponential functions were used for some sites. The choice of function was based on how well the line or curve fitted the data, and most attention was given to the proximity of the resulting values, or, if data were extrapolated, to the relevant end of the range.

Data

The handbook by Hicks and Mason (1991) provides photos and hydraulic and bed-material data from 78 New Zealand river reaches, collected by field teams from the National Institute of Water and Atmospheric Research (NIWA). The handbook was produced to provide reference reaches for estimating roughness coefficients for

Table 1A Substrate particle size percentiles (d_{50} and d_{84}), the median flow (*Q50*), mean flow (*MF*) and mean annual maximum flow (*MAM*) for the period of record, the maximum rated flow (MaxQ) in Hicks and Mason (1991), average friction slope (S_f) and slope correction factor calculated from equation (7)

Site	Name	d_{50} mm	d_{84} mm	From date	To date	Q50 m^3/s	MF m^3/s	MAM m^3/s	MaxQ m^3/s	Average S_f	Slope correction
8604	Orere at Bridge	30	67	06-29-78	12-31-95	0.65	1.00	44.8	50.6	0.00276	0.9961
15901	Waioeka at Gorge Cableway	45	88	03-17-58	12-31-95	16.7	31.8	719	717	0.00346	0.9951
29250	Ruakokapatuna at Iraia	45	119	05-29-69	10-19-00	0.24	0.68	29.7	15.2	0.00586	0.9916
29808	Hutt at Kaitoke	86	212	12-21-67	12-31-95	4.33	7.64	258	104	0.00383	0.9945
32702	Rangitikei at Mangaweka	31	91	04-29-69	10-04-00	45.6	62.7	706	542	0.00347	0.9950
33107	Whangaehu at Karioi	28	120	04-03-69	10-04-00	13.2	14.6	93.2	61	0.00215	0.9969
46609	Mangere at Kara Weir	19.4	39.6	04-24-75	01-08-93	0.18	0.33	45.3	87	0.00303	0.9957
57014	Stanley Brook at Barkers	32	106	12-31-69	05-30-94	0.36	1.17	56.3	36.9	0.00547	0.9922
67602	Huka Huka at Lathams Bridge	94	258	12-14-87	12-31-95	0.10	0.23	10.1	8.17	0.03959	0.9427
71129	Forks at Balmoral	23.5	104	05-21-75	12-31-95	2.48	3.20	23.3	8	0.00522	0.9925
71135	Jollie at Mount Cook Station	33	90	12-07-64	12-31-95	6.43	8.16	78.6	31.3	0.00886	0.9873
75290	Cardrona at Albert-town	24.3	78	07-28-78	10-04-00	2.08	2.96	57.6	7.61	0.00814	0.9883
89103	Okarito at Lake Wahapo	397	800	07-16-96	10-09-00	0.21	6.15	503	282	0.03816	0.9448
90605	Butchers Creek at Lake Kaniere	69.3	168	07-15-71	01-27-94	0.08	0.35	27.6	18.9	0.01415	0.9797
91401	Grey at Dobson	33	67	07-24-68	10-10-00	249	364	3718	3220	0.00093	0.9987
93208	Buller at Woolfs	56.3	182	07-15-71	01-27-94	187	257	2897	2810	0.00066	0.9991
93209	Maruia at Falls	8.9	33	12-06-63	08-23-91	39.8	59.0	848	511	0.00063	0.9991
1043459	Tongariro at Turangi	27	150	01-01-57	10-11-00	30.3	40.3	438	161	0.00246	0.9965

Site	Name	d_{50} mm	d_{84} mm	From date	To date	Q50 m^3/s	MF m^3/s	MAM m^3/s	MaxQ m^3/s	Average S_f	Slope correction
4901	Ngunguru at Dugmores Rock	36	96	08-22-69	01-21-94	0.21	0.40	57.9	29.3	0.00481	0.9931
34305	Patea at McColls Bridge	28	120	11-13-86	07-11-95	15.2	28.2	272	218	0.00112	0.9984
29809	Hutt at Taita Gorge	90	170	03-16-79	01-23-98	14.9	25.2	922	298	0.00191	0.9973
30516	Mill Creek at Papanui	18	47	04-24-69	12-31-95	0.05	0.13	7.6	8.52	0.00262	0.9962
31807	Otaki at Pukehinau	11.3	37	07-17-80	12-31-95	16.6	31.9	914	123	0.00025	0.9996
37503	Kapoaiaia at Lighthouse	78	212	02-18-86	12-31-95	0.70	1.10	29	5.2	0.00976	0.9860
47804	Waipapa at Forest Ranger	46.3	91	03-31-78	12-31-95	2.12	4.34	233	59.3	0.00234	0.9967
52916	Cobb at Trilobite	70	200	05-01-69	10-01-00	1.89	3.82	97.3	40.4	0.00219	0.9969
1903	Oruru at Saleyards	17.3	45	12-15-88	12-31-95	1.23	2.15	58.9	14.2	0.00105	0.9985
9140	Piako at Paeroa-Tahuna Bridge	0.8	1.4	07-03-42	01-31-00	2.86	6.82	88.9	18.9	0.00011	0.9998
23150	Ngaruroro at Chesterhope Bridge	54	70	11-25-76	12-31-95	25.5	42.6	877	563	0.00072	0.9990
33301	Wanganui at Paetawa	25	56	07-25-57	12-31-95	129	215	2251	2960	0.00026	0.9996
33316	Ongarue at Taringamotu	23	57	08-05-62	09-30-00	24.6	35.0	279	241	0.00053	0.9992
58902	Pelorus at Bryants	47	175	10-26-77	12-31-95	8.30	20.7	941	290	0.00291	0.9958
62105	Clarence at Jollies	104	200	12-31-59	12-31-98	10.9	15.1	205	120	0.00303	0.9957
66602	Avon at Gloucester Street Bridge	35	57	07-07-80	12-18-00	1.71	1.90	15.6	17.3	0.00090	0.9987
71103	Hakataramea above MHB	35	57	11-26-63	01-04-01	3.57	6.00	187	22.8	0.00109	0.9984
74347	Longaburn at Gorge (Downstream)	20.3	46	07-02-80	11-20-90	1.03	1.54	43	5.82	0.00172	0.9975
75232	Pomahaka at Burkes Ford	112	178	08-04-61	12-31-95	17.7	27.3	463	114	0.00041	0.9994
75259	Fraser at Old Man Range	89	208	05-27-69	12-31-95	1.29	2.26	37.6	5.23	0.00800	0.9885
80201	Rowallanburn at Old Mill	125	250	03-28-89	10-07-93	0.72	1.25	27.8	14.7	0.00090	0.9987
1014641	Ngongotaha at SH5 Bridge	8.3	22	05-21-75	12-31-95	1.59	1.75	22	27.7	0.00096	0.9986

Table 1B Critical shear stresses for d_{50} and d_{84} size particles ($\tau_c(d_{50})$ and $\tau_c(d_{84})$, respectively), bed-moving flows ($Q_B(d_{50})$ and $Q_B(d_{84})$) and information on the fitted τ' versus Q relationship.

Site	Name	Critical shear stresses $\tau_c d(_{50})$ N/m^2	$\tau_c d(_{84})$ N/m^2	Regressions[1] Type	a	b	c	R^2	Bed-moving flows $Q_B(d_{50})$ m^3/s	$Q_B(d_{84})$ m^3/s	Notes
8604	Orere at Bridge	21.77	28.83	Power	0.0801	1.7914		0.960	20.0	33.0	Acceptable
15901	Waioeka at Gorge Cableway	32.62	41.24	Power	0.1397	1.9071		0.964	108	168	Acceptable
29250	Ruakokapatuna at Iraia	32.50	45.68	Polynomial	0.0087	-0.0696	0.4005	0.982	7.33	15.4	Acceptable
29808	Hutt at Kaitoke	62.30	85.43	Polynomial	0.0113	0.7351	-2.0030	0.993	87.6	143	Acceptable
32702	Rangitikei at Mangaweka	22.47	32.75	Power	0.0245	2.5010		0.950	58.8	151	Acceptable
33107	Whangaehu at Karioi	20.33	33.84	Power	0.0730	1.8785		0.991	20.9	54.5	Acceptable
46609	Mangere at Kara Weir	14.07	18.06	Polynomial	0.0972	2.2972	-1.2669	0.990	50.3	71.9	Acceptable
57014	Stanley Brook at Barkers	23.13	35.17	Polynomial	0.0116	0.0291	-0.3285	0.998	6.55	15.0	Acceptable
67602	Huka Huka at Lathams Bridge	64.55	91.91	Linear	0.0669	-0.7744		0.976	3.54	5.37	Acceptable
71129	Forks at Balmoral	16.99	28.59	Power	0.0064	2.1378		0.998	2.72	8.29	Acceptable
71135	Jollie at Mount Cook Station	23.73	33.72	Power	0.1217	1.3424		0.892	8.55	13.7	Acceptable
75290	Cardrona at Albert-town	17.49	26.31	Power	0.0007	2.6176		0.993	1.34	3.90	Acceptable
89103	Okarito at Lake Wahapo	273.2	349.15	Polynomial	0.0023	0.0061	0.5333	0.998	174	283	Acceptable
90605	Butchers Creek at Lake Kaniere	49.45	67.42	Power	0.0006	2.2101		0.966	3.3	6.6	Acceptable
91401	Grey at Dobson	24.01	30.76	Power	6.8215	1.5979		0.969	1095	1627	Acceptable
93208	Buller at Woolfs	40.97	61.77	Power	9.6048	1.3967		0.967	1716	3046	Acceptable
93209	Maruia at Falls	6.48	10.25	Power	16.2558	1.0255		0.999	110	177	Acceptable
1043459	Tongariro at Turangi	19.60	35.72	Exponential	17.2871	0.0356		0.996	34.7	61.7	Acceptable

		Critical shear stresses		Regressions[1]					Bed-moving flows		Notes
Site	Name	$\tau_c d(_{50})$ N/m^2	$\tau_c d(_{84})$ N/m^2	Type	a	b	c	R^2	$Q_B(d_{50})$ m^3/s	$Q_B(d_{84})$ m^3/s	
4901	Ngunguru at Dugmores Rock	26.04	36.71	Exponential	0.4295	0.1589		0.962	26.9	147	$Q_B(d_{84})$>>$MaxQ$
34305	Patea at McColls Bridge	20.36	33.89	Polynomial	0.2588	4.7487	2.4389	1.000	206	461	$Q_B(d_{84})$>>$MaxQ$
29809	Hutt at Taita Gorge	65.38	81.68	Power	0.3178	1.8186		0.996	636	954	$Q_B(d_{50})$>>MaxQ
30516	Mill Creek at Papanui	13.06	18.28	Polynomial	0.0631	0.0927	0.0798	0.999	12.1	22.9	$Q_B(d_{50})$>>$MaxQ$
31807	Otaki at Pukehinau	8.23	12.46	Power	45.7661	0.7077		0.985	203	273	$Q_B(d_{50})$>>$MaxQ$
37503	Kapoaiaia at Lighthouse	56.02	79.49	Power	0.0234	1.4994		0.926	9.8	16.6	$Q_B(d_{50})$>>$MaxQ$
47804	Waipapa at Forest Ranger	33.61	42.58	Power	0.4843	1.5176		0.997	100	144	$Q_B(d_{50})$>>$MaxQ$
52916	Cobb at Trilobite	50.83	73.40	Power	0.6721	1.1021		0.982	51.0	76.5	$Q_B(d_{50})$>>$MaxQ$
1903	Oruru at Saleyards	12.58	17.58	No acceptable solution							
9140	Piako at Paeroa-Tahuna Bridge	0.58	0.71	No acceptable solution							
23150	Ngaruroro at Chesterhope Bridge	39.29	43.03	No acceptable solution							
33301	Wanganui at Paetawa	18.20	24.14	No acceptable solution							
33316	Ongarue at Taringamotu	16.74	23.00	No acceptable solution							
58902	Pelorus at Bryants	34.09	54.01	No acceptable solution							
62105	Clarence at Jollies	75.42	94.82	No acceptable solution							
66602	Avon at Gloucester Street Bridge	25.46	30.20	No acceptable solution							
71103	Hakataramea above MHB	25.45	30.19	No acceptable solution							
74347	Longaburn at Gorge (Downstream)	14.75	19.64	No acceptable solution							
75232	Pomahaka at Burkes Ford	81.53	95.88	No acceptable solution							
75259	Fraser at Old Man Range	64.08	86.26	No acceptable solution							
80201	Rowallanburn at Old Mill	90.93	115.90	No acceptable solution							
1014641	Ngongotaha at SH5 Bridge	6.04	8.49	No acceptable solution							

(1) Equations for regressions are:

Power $Q_B = a\tau^b$

Linear $Q_B = a\tau + b$

Exponential $Q_B = a \exp(b\tau)$

Polynomial $Q_B = a\tau^2 + b\tau + c$

channels. We used data from 40 sites from which we were able to obtain flow data (Table 1).

Of the hydraulic data reported in the book, we used values of flow (Q), friction slope (S_f), reach average hydraulic radius (R) and mean velocity (V). The values were calculated from measurements (see descriptions of calculations in Hicks and Mason, 1991) in typically 3–5 cross-sections per reach for each visit, and each site was visited typically 6–7 times (varying from 2 to 14) to cover as wide a range of flows as possible. The size distribution of the surface sediments was obtained using the Wolman method (Wolman, 1954) for gravel-bed rivers, and sieve analysis of samples for sand-bed rivers. The 50 and the 84 percentiles (d_{50} and d_{84}) were used in this study.

Time-series of flow data for the 40 sites were collected by NIWA, regional councils and electricity corporations (see Acknowledgements). We used instantaneous (15-minute interval) data to calculate the median flow ($Q50$), the mean flow (MF) and the mean annual maximum flow (MAM). The mean annual maximum flow values calculated here differ less than 10% from the values reported by Hicks and Mason (1991), except for newer sites where most of the record years are after the production of the handbook.

Examples

Two examples (a big river and a small stream) are used to illustrate the calculations.

93209 Maruia at Falls

The river is relatively large at this site (Fig. 1a) with a mean flow of 59 m^3/s (see values of median flow, mean flow, and the mean annual maximum flow in Figure 1b or Table 1). The bed substrate is gravel with a d_{50} of 8.9 mm and a d_{84} of 33 mm (Table 1).

Data were collected by NIWA 5 times at 5 cross-sections over a 502 m long reach (Table 2). The average value of S_f is 0.00063. The critical shear stresses τ'_{csi} to move particles of size d_{84} and size d_{50} are calculated from equation (8) as 10.25 N/m^2 and 6.48 N/m^2, respectively. For each flow gauging, values for τ' and τ are calculated from equations (11) and (2), respectively. At this site, the calculated values for τ' are lower than the total shear stress for all gauged flows, indicating that grain roughness is responsible for 86% of the total drag, on average. A power relationship is used to relate τ' and Q (Fig. 1c). Using this best-fit curve, the bed-moving flows are calculated as $Q_B(d_{84})$ = 177 m^3/s and $Q_B(d_{50})$ = 110 m^3/s.

Figure 1b shows the 1990 hydrograph for the Maruia River at Falls, with indications of the median flow, $Q_B(d_{84})$ and $Q_B(d_{50})$ for the period of record. Thus, for this river $Q_B(d_{84})$ is 4.4 times the median flow, 3.0 times the mean flow and 0.21 times the mean annual maximum flow, while $Q_B(d_{50})$ is 2.8 times the median flow, 1.9 times the mean flow and 0.13 times the mean annual maximum flow.

90605 Butchers Creek at Lake Kaniere

This stream is relatively small (Fig. 2a), with a mean flow of 0.35 m^3/s (see other flow statistics in Fig. 2b or Table 1). The bed substrate is relatively coarse, with a d_{50} of 69.3 mm (cobble size) and a d_{84} of 168 mm (boulder size) (Table 1).

Data were collected by NIWA 12 times at 5 cross-sections over a 103 m reach (Table 3). S_f is relatively high, with an average value of 0.014. The critical shear stresses τ'_{csi} to move particles of size d_{84} and size d_{50} are calculated as 67.42 N/m^2 and 49.45 N/m^2, respectively. Calculated τ' values from equation (11) are around 10% of τ for flows lower than 0.1 m^3/s, approximately 80% for flows around 2 m^3/s, and above 100% for flows higher than 4 m^3/s. Thus, the ratio increases with flow at this site, perhaps due

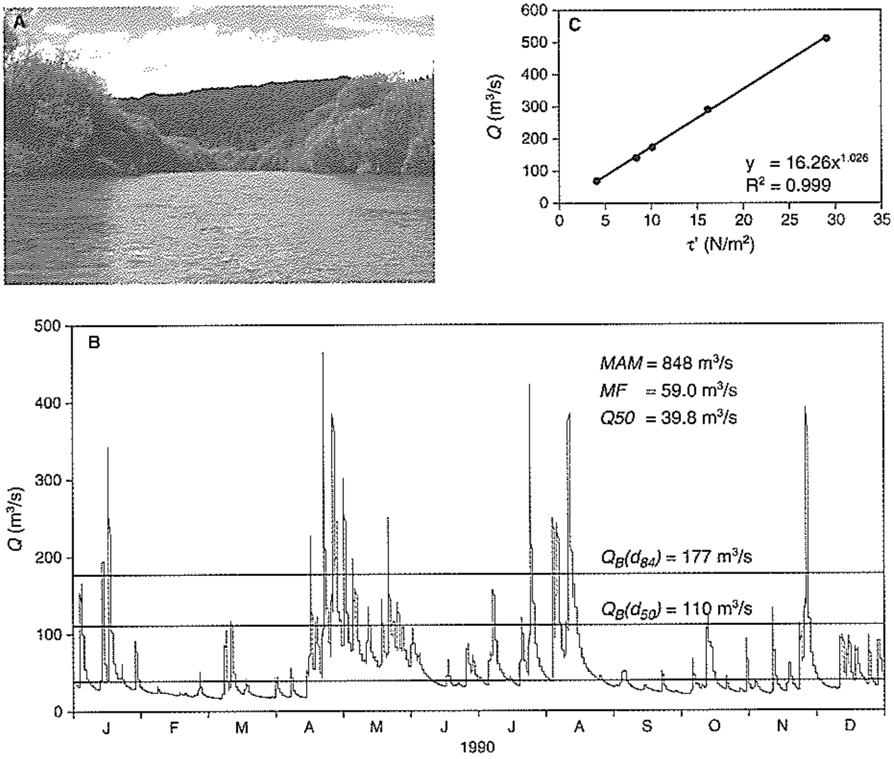

Figure 1 Maruia at Falls (site no. 93209), (a) view downstream from top cross-section (with permission from NIWA); (b) daily streamflows during 1990 and values of the median flow (*Q50*), the mean flow (*MF*) and the mean annual maximum flow (*MAM*) for 1963-1991, and the calculated bed-moving flows ($Q_B(d_{84})$ and $Q_B(d_{50})$); (c) flow (*Q*) versus grain shear stress (τ') and fitted power function for a 502 m long reach (data from Hicks and Mason, 1991).

Table 2 Flow rating data for site 93209 Maruia at Falls (from Hicks and Mason, 1991) with hydraulic radius (*R*), flow (*Q*), friction slope (S_f), mean velocity (*V*), calculated friction factor (*f*), calculated grain shear stress (τ'), total shear stress (τ), and adjusted τ' used to calculate bed-moving flows (the minimum of calculated τ' and τ).

R (m)	*Q* (m³/s)	S_f	*V* (m/s)	*f*	τ' **Eq.(11)** (N/m²)	τ **Eq.(2)** (N/m²)	τ' **Adjusted** (N/m²)
1.58	69.5	0.00033	0.81	0.04986	4.09	5.11	4.09
2.04	141	0.00044	1.22	0.04520	8.41	8.81	8.41
2.22	174	0.00055	1.36	0.04380	10.13	11.98	10.13
2.69	290	0.00073	1.78	0.04085	16.18	19.26	16.18
3.12	511	0.00109	2.45	0.03878	29.09	33.36	29.09

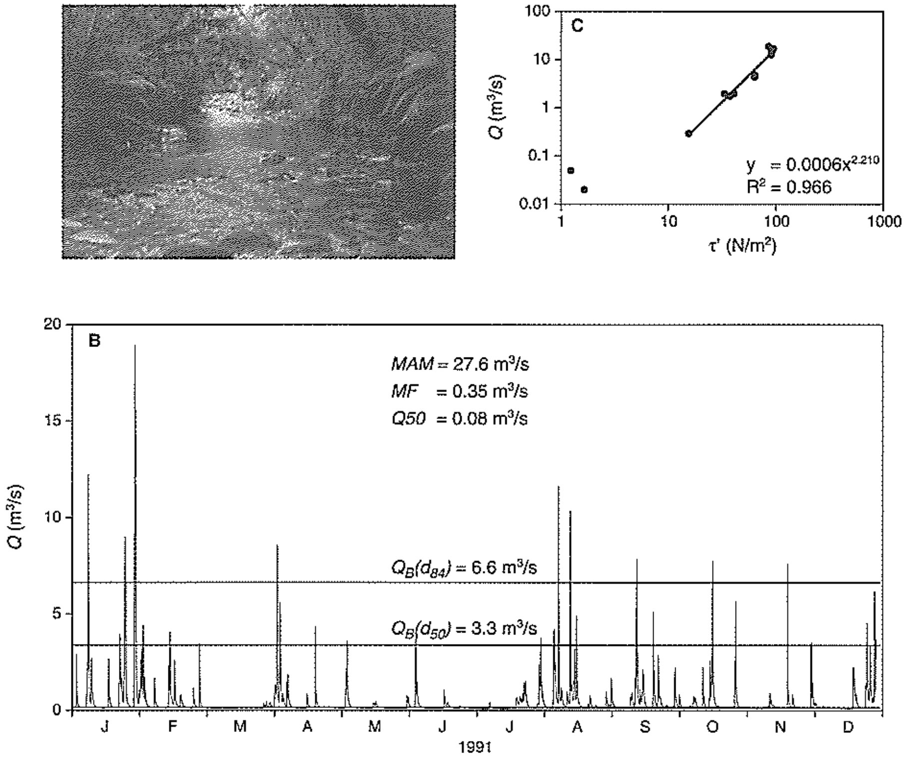

Figure 2 Butchers Creek at Lake Kaniere (site no. 90605), (a) view upstream from top cross-section (with permission from NIWA); (b) daily streamflows during 1991 and values of the median flow (*Q50*), the mean flow (*MF*) and the mean annual maximum flow (*MAM*) for 1971-1994, and the calculated bed-moving flows ($Q_B(d_{84})$ and $Q_B(d_{50})$); (c) flow (*Q*) versus grain shear stress (τ') and fitted power function for a 502 m long reach (data from Hicks and Mason, 1991). The two lower points were not used to fit the power function.

to backwater effects. For flows higher than 4 m^3/s the values of τ' are set equal to the values of τ calculated from equation (2). The resulting values are plotted (Fig. 2c) and a power relationship is fitted to all points except the ones with flows lower than 0.1 m^3/s. From this the bed-moving flows are calculated as $Q_B(d_{84}) = 6.6$ m^3/s and $Q_B(d_{50}) = 3.3$ m^3/s.

The 1991 hydrograph (Fig. 2b) shows a flow regime somewhat different from the previous example, with relatively low values of the mean flow, and especially the median flow. The values of $QB(d_{84})$ is 83 times the median flow, 19 times the mean flow, and 0.24 times the mean annual maximum flow, while $Q_B(d_{50})$ is 41 times the median flow, 9 times the mean flow and 0.12 times the mean annual maximum flow. Compared to the previous example, the bed-moving flows are similar relative to the mean annual maximum flow, but very different relative to the median flow and the mean flow.

Results

Descriptions of bed substrate

Most of the analysed river reaches have relatively coarse bed substrate, with d_{50} in either gravel size range (8–64 mm, 28 reaches) or cobble size range (64–264 mm, 10

Table 3 Flow rating data for site 90605 Butchers Creek at Lake Kaniere (from Hicks and Mason, 1991) with hydraulic radius (*R*), flow (*Q*), friction slope (S_f), mean velocity (*V*), calculated friction factor (*f*), calculated grain shear stress (τ'), total shear stress (τ), and adjusted τ' used to calculate bed-moving flows (the minimum of calculated τ' and τ).

R (m)	*Q* (m^3/s)	S_f	*V* (m/s)	*f'*	τ' Eq.(11) (N/m^2)	τ Eq.(2) (N/m^2)	τ' Adjusted (N/m^2)
0.10	0.02	0.0134	0.07	2.68445	1.64	13.15	1.64
0.14	0.05	0.0152	0.09	1.21564	1.23	20.88	1.23
0.16	0.29	0.0146	0.36	0.95236	15.43	22.92	15.43
0.31	1.75	0.0146	0.88	0.38684	37.45	44.40	37.45
0.34	1.95	0.0150	0.87	0.35044	33.16	50.03	33.16
0.33	1.99	0.0147	0.95	0.36162	40.80	47.59	40.80
0.44	4.31	0.0147	1.38	0.27224	64.81	63.45	63.45
0.45	4.80	0.0144	1.48	0.26670	74.01	63.57	63.57
0.67	12.6	0.0138	2.11	0.19115	106.4	90.70	90.70
0.68	14.5	0.0138	2.32	0.18898	127.1	92.06	92.06
0.72	16.7	0.0135	2.53	0.18097	144.8	95.35	95.35
0.72	18.9	0.0121	2.90	0.18097	190.2	85.46	85.46

reaches) (Table 1). One reach (9140 Piako) has sand and one (89103 Okarito) has boulders as substrate. The average d_{84}/d_{50} ratio is 2.7 and the maximum ratio is 5.6 (1043459 Tongariro). Thus, the d_{84}/d_{50} values do not exceed the limit for which equation (5) was found to be applicable by Komar (1989). However, several rivers have particles with diameters larger than 100 mm. Thus, some of the rivers used in this study have coarser bed material and also steeper slopes than the ones used by Komar to derive the equation.

Deriving values for bed-moving flows (Q_B)

In calculating $Q_B(d_{50})$ and $Q_B(d_{84})$ for the 40 river reaches, the following results were obtained:

- The value of $(1 - \tan(S_{fB}) / \tan(35°))$ is close to 1 for all sites; thus, the correction for steep bed slopes does not have much influence on the results, and equation (6) is a good approximation to equation (8) for most sites. The average value of $(1 - \tan(S_{fB}) / \tan(35°))$ is 0.99, and only two reaches have values below 0.97 (0.943 for 67602 Huka Huka and 0.945 for 89103 Okarito, the two steepest reaches with S_f close to 4%).
- Linked to the above point, varying θ between 25° (representing substrate finer than gravel) and 40° (representing material coarser than gravel) in $(1 - \tan(S_{fB}) / \tan(\theta))$ has the largest influence for the steeper sites. The change in the slope correction factor is –3% for $\theta = 25°$ and +1% for $\theta = 40°$ for the two steepest sites, 67602 Huka Huka and 89103 Okarito. The average change in slope correction factor for the 40 sites is –0.4% and +0.1% for $\theta = 25°$ and 40°, respectively. The average resulting change in calculated $Q_B(d_{84})$ is –0.6% and +0.3% for $\theta = 25°$ and 40°, respectively.
- For 14 sites, the τ' versus *Q* relationship is either not well defined or has insufficient data points to construct an accurate

regression curve, or the calculated bed-moving flows are far in excess of the measured flows. Calculations for these sites are considered unreliable, and the results are discarded.

- Of the remaining 26 sites, the calculated bed-moving flow $Q_B(d_{50})$ is within the range of flow values measured by Hicks and Mason (1991) at 20 sites, and higher than the maximum rated flow at the other 6 sites. $Q_B(d_{84})$ is within or acceptably close to (within 20%) the maximum rated flow at 18 sites, and higher at the other 8 sites.
- Of the 26 sites where Q_B has been determined, the calculated grain shear stress τ' at Q_B is less than total shear stress τ for 13 sites.

How high is the bed-moving flow?

Figure 3a-c shows plots of $Q_B(d_{50})$ versus the median flow, the mean flow and the mean annual maximum flow, respectively, and Figure 4a-c shows plots of $Q_B(d_{84})$ versus the

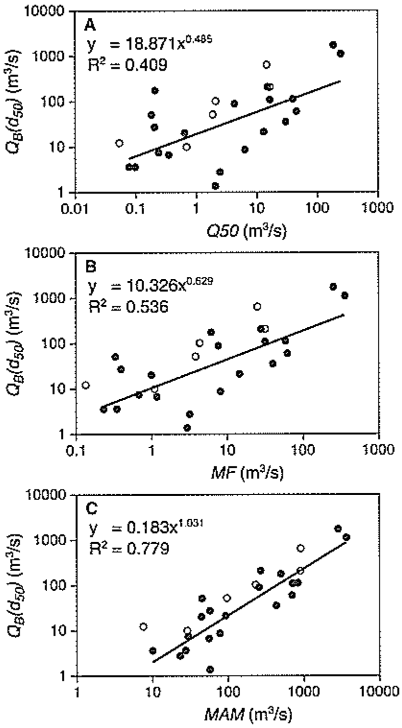

Figure 3 Calculated bed-moving flow ($Q_B(d_{50})$) for d_{50} versus (a) median flow (*Q50*), (b) mean flow (*MF*) and (c) mean annual maximum flow (*MAM*) in 26 New Zealand rivers reaches, with best-fit power functions (straight lines on log-log plots) based on the solid points. Open circles indicate that the calculated $Q_B(d_{50})$ exceeds the maximum flow in the ratings by Hicks and Mason (1991).

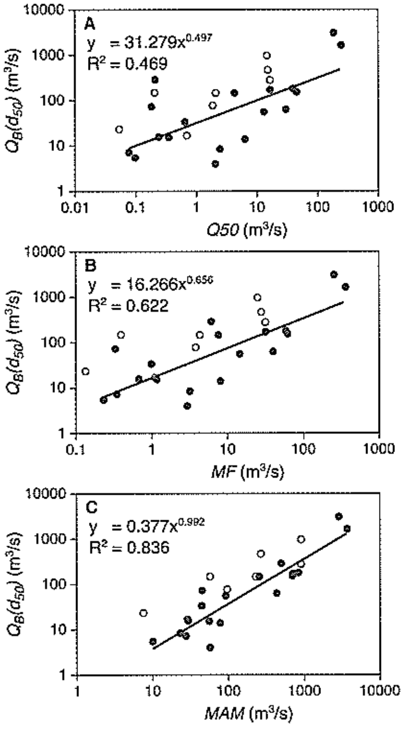

Figure 4 Calculated bed-moving flow ($Q_B(d_{84})$) for d_{84} versus (a) median flow (*Q50*), (b) mean flow (*MF*) and (c) mean annual maximum flow (*MAM*) in 26 New Zealand rivers reaches, with best-fit power functions (straight lines on log-log plots) based on the solid points. Open circles indicate that the calculated $Q_B(d_{84})$ exceeds the maximum flow in the ratings by Hicks and Mason (1991) by more than 20%.

median flow, the mean flow and the mean annual maximum flow, respectively. Note that both axes have logarithmic scales. The solid circles in Figure 3 are the data points from the 20 sites for which the calculated $Q_B(d_{50})$ is less than the maximum rated Q as measured by Hicks and Mason (1991). The open circles are data points from the 6 sites where the τ' versus Q relationship was extrapolated beyond the highest rated flow; the values indicated by the open circles are considered unreliable. The solid circles in Figure 4 are the data points from the 18 sites for which the calculated $Q_B(d_{84})$ is less than or acceptably close to (within 20%) of the highest rated flow. The open circles are for the 8 sites where the calculated $Q_B(d_{84})$ is considerably higher than the maximum rated flow, and these are considered unreliable. In Figures 3 and 4, the open circles appear to lie higher than the solid circles. Only the values indicated by the solid circles (where $Q_B(d_{50})$ or $Q_B(d_{84})$ is within the rated values or acceptably close) were used to calculate the regressions indicated by the solid lines.

All six plots indicate a positive relationship. Calculated bed-moving flows correlate strongly with all three flow parameters (Table 4); R^2 varies between 0.41 and 0.84 and is highest for the $Q_B(d_{84})$ versus mean annual maximum flow relationship. The exponent is smaller than 1.0 for the median flow and mean flow plots, and approximately 1.0 for the mean annual maximum flow plots (almost a linear relationship). Correlations are stronger for $Q_B(d_{84})$ than for $Q_B(d_{50})$. Although the correlations between Q_B and the flow parameters (in particular mean annual maximum flow) are strong, the variation is too large to allow the model to be used for prediction.

Discussions and Conclusions

Calculation of the bed-moving flows, here defined as the critical flows able to move d_{50} and d_{84}, has been attempted for 40 rivers reaches and solutions have been found in 26 cases. For 18 of these sites, the calculated bed-moving flows are less than or close to the maximum rated flow for that site (from the ratings given by Hicks and Mason, 1991). Failure to obtain results in 14 cases is due to a poor relationship between τ' and Q.

The strongest correlation between calculated bed-moving flows (for both d_{50} and d_{84}) is with the mean annual maximum flows (Table 4). The best-fit relationship is nearly linear for both sediment size fractions. This finding supports the view that bed movement in New Zealand gravel-bed rivers is related to floods rather than mean or median flows.

The uncertainty related to the calculated bed-moving flow has not been quantified here. It is clear that any error on the measured values of friction slope, hydraulic radius, mean velocity and discharge is carried through to the final result. Hicks and Mason (1991) states that the water level has been measured with an accuracy of ± 3 mm. A typical distance between cross-sections is 100 m, which means that a water level slope

Table 4 Best-fit power expressions for bed-moving flows ($Q_B(d_{50})$ and $Q_B(d_{84})$) for particle sizes d_{50} and d_{84} as functions of the median flow (*Q50*), the mean flow (*MF*), and the mean annual maximum flow (*MAM*).

	$Q_B(d_{50})$	R^2	$Q_B(d_{84})$	R^2
Q50	$18.871\,(Q50)^{0.485}$	0.409	$31.279\,(Q50)^{0.497}$	0.469
MF	$10.326\,(MF)^{0.629}$	0.536	$16.266\,(MF)^{0.656}$	0.622
MAM	$0.183\,(MAM)^{1.031}$	0.779	$0.377\,(MAM)^{0.992}$	0.836

would have an accuracy of ± 6 mm/100 m (less than 0.01%). The uncertainty related to a flow gauging is estimated as ± 8% by Hicks and Mason (1991). This is not a large error compared to the uncertainties involved in using a relatively simple formula to calculate bed-moving flows. A further complication is that reach-averaged values are used for both flow and sediment parameters. In reality, sediment size and grain shear stress will show considerable spatial variation over a river reach. Sediment movement will thus occur at different flow rates at different points within the reach.

How close the calculated values are to the true bed-moving flows is unknown, as no attempts have been made here to match observations with the calculated results. This would be a highly interesting future project, although difficult due to the inherent difficulties in measuring bed transport.

An interesting study was carried out by Lorang and Hauer (2003), who used Komar's equation (without the correction for steep slopes that we used) on 33 river reaches from Hicks and Mason (1991) with steep bed slopes ($S > 0.002$). They calculated the ratio (ξ) of the shear stress for the maximum particle size (d_{max}) at bank-full flow to the critical shear stress for d_{max}. They found that the ratio ξ was lower than 1.0 for 27 of the 33 reaches and seemed to decrease with d_{84}, but not with d_{max}/d_{50}. Based on this result and the assumption that bank-full flow mobilises all bed material (i.e., that ξ should be higher than 1.0), they suggest that the critical shear stress is overestimated by using a value of 0.045 for τ^*_{c50}, and that it might be more appropriate to use a value of 0.02 as suggested by Andrews (1983). Lorang and Hauer (2003) speculated that the deviation between the calculated and expected values could be due to momentum exchange between colliding particles, especially for coarse substrates (cobble and boulder), and variations in velocity, two phenomena that are not considered in the competence formula. If their suggestions are correct, we would have overestimated the bed-moving flow by using a value of 0.045 for τ^*_{c50} for rivers with a coarse substrate. Reducing the value of τ^*_{c50} from 0.045 to 0.020 will reduce the calculated values of Q_B by a factor of 2–6. However, it is yet to be tested whether bank-full flow does mobilise all bed material (whether ξ should be higher than 1.0), the assumption on which Lorang and Hauer's results are based. A further complication to this approach is that it can be difficult to identify the location of banks in New Zealand gravel-bed rivers and the concept of bank-full flow becomes meaningless.

The separation of total bed shear stress into grain and form components is a common procedure for sediment transport calculations (Einstein, 1942; Meyer-Peter and Muller, 1948; Wilcock and Kenworthy, 2002). However, the studies by both Lorang and Hauer (2003) and Duncan and Biggs (1998) used total stress rather than grain shear stress when determining the threshold for movement. If we did not separate the total shear stress into grain and form components, we would obtain much lower estimates of the bed-moving flows. More precisely, if the total shear stress was used to estimate the bed-moving flow, then the $Q_B(d_{84})$ estimates would be on average about 20% of the mean annual maximum (with the relationship between MAM and Q_B being nearly linear), compared to the 38% obtained using the calculated grain shear stress as performed here. This is a significant difference (approximately 90% of the lower value) in predicted flow for bed instability.

Unfortunately, there appears to be no direct method of accurately calculating grain shear stress in a natural gravel-bed river. In this present study, an empirical relationship derived from river data (Hey, 1979) was used to estimate the grain shear stress component. At some sites, the estimated grain shear stress exceeded the total shear stress calculated from the field measurements. Our method for these sites, where predicted grain stress exceeded total stress, was to assume that all the stress was due to grain roughness, and ignore any contribution of form drag. This is a simplification that may result in erroneous estimates of the bed-moving flows.

Although equation (8) is based on observations, it does make use of only two percentiles (d_{50} and d_{84}) of the substrate. Armouring, siltation and other features of the bed surface are not taken into account unless they are reflected in the two percentiles, and factors such as bed packing, imbrication, and particle shape and orientation are not considered.

The method presented here gives a first approximation of the bed-moving flow. Improved estimates would require field measurements of critical shear stress or bed-motion observations for each river reach. It is highly recommended that field observations be carried out if the bed-moving flow in a particular river is of interest.

Bearing in mind that the bed-moving flow was calculated from a competence formula (using a value of 0.045 for τ^*_{c50}) and not observed, the results suggest that the bed-moving flow is higher than three times the median flow for many New Zealand rivers. The results indicate that it is not realistic to expect that the bed-moving flow can be calculated easily from a flow statistic.

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