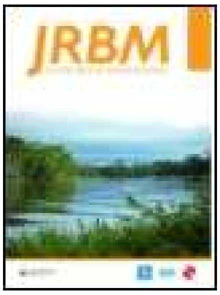

International Journal of River Basin Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trbm20

Towards understanding river sediment dynamics as a basis for improved catchment, channel, and coastal management: the case of the Motueka catchment, Nelson, New Zealand

Ian C. Fuller Senior Lecturer[a], Les R. Basher Senior Scientist, Landcare Research[b] & D. Murray Hicks Principal Scientist[c]

[a] Physical Geography Group, Institute of Agriculture & Environment, Massey University, Palmerston North, New Zealand.

[b] Nelson, New Zealand. Email:

[c] NIWA, Christchurch, New Zealand. Email:

Accepted author version posted online: 22 Jan 2014.Published online: 18 Mar 2014.

Intl. J. River Basin Management iFirst, 2014, 1–18

Research paper

Towards understanding river sediment dynamics as a basis for improved catchment, channel, and coastal management: the case of the Motueka catchment, Nelson, New Zealand

IAN C. FULLER, *Senior Lecturer, Physical Geography Group, Institute of Agriculture & Environment, Massey University, Palmerston North, New Zealand. Email: i.c.fuller@massey.ac.nz (author for correspondence)*

LES R. BASHER, *Senior Scientist, Landcare Research, Nelson, New Zealand. Email: basherl@landcareresearch.co.nz*

D. MURRAY HICKS, *Principal Scientist, NIWA, Christchurch, New Zealand. Email: murray.hicks@niwa.co.nz*

ABSTRACT
This paper brings together work in the Motueka catchment that has focused on both suspended sediment data and bedload transfers to provide a more holistic understanding of sediment dynamics in the catchment to inform effective river management. The annual suspended sediment load averages 349,000 t and shows considerable temporal variability (49,000 t to 1.7 Mt). Event yields may increase by an order of magnitude in response to single high magnitude storm events. Much of the sediment is generated from high rainfall areas of the catchment under indigenous forest and grassland. Short-term studies show pasture areas have a higher specific sediment yield than production forest, but that forest harvesting leads to a short-term increase in yield. Bedload transfers assessed via morphological budgeting from digital elevation model (DEM) differencing in selected reaches of the upper Motueka reveal similarly highly variable transfers at an annual scale, reflecting the magnitude and frequency of competent flow events. Longer term mean bed-level (MBL) changes demonstrate a high degree of spatial variability in the upper Motueka. Overall, DEMs of difference and longer term MBL changes both reveal a net channel degradation and export of bedload in the mainstem of the upper Motueka. Suspended sediment data also suggest an overall reduction in sediment yield from the catchment, suggesting a catchment-wide limitation of sediment supply, or a period of lower flows reducing sediment mobilization. This understanding has informed on issues such as the role of river channel management and catchment land use on in-stream ecosystems, coastal erosion, and shelf water quality and fisheries. Future river management, if it is to be effective, needs to recognize the history of this system, its likely longer term trajectory, and its linkages with the coast.

Keywords: Suspended sediment; bedload; sediment yield; DEM; gravel extraction

1 Introduction

For improved environmental outcomes, holistic approaches to land and water management are needed (Fenemor *et al*. 2011). Understanding sediment dynamics is essential for effective river management (Raven *et al*. 2010a, 2010b) because there is a strong link between catchment sediment supply, sediment storage in channels, flood risk and sediment impacts on river health (Lane *et al*. 2007). River management is most likely to be effective, efficient and sustainable where strategies take into account the natural character of a system (Brierley and Fryirs 2000, 2009). Natural character reflects the interaction of water, sediment and vegetation that shapes the structure and function of a river in its natural, unmanaged state, which thereby includes sediment transfers operating within the catchment. However, traditional river engineering has taken little account of either natural character or sediment dynamics and frequently banks have been 'protected' and channels straightened without proper consideration of the interactions between the channel and sediment transfer (Davies 1997, McDonald *et al*. 2004, Fuller *et al*. 2012, Fuller and Basher 2013). Furthermore, the norm for river channels is instability (Raven *et al*. 2010a) and change should be anticipated and incorporated into river management and engineering design (Newson and Large 2006). However, when, as is often the case, such dynamics are not taken into account, the channel is no longer able to adjust naturally and sediment dynamics are altered. This can lead to unintended consequences of river management, such as loss of habitat heterogeneity (Edwards *et al*.

Received 24 January 2013. Accepted 9 January 2014.

ISSN 1571-5124 print/ISSN 1814-2060 online
http://dx.doi.org/10.1080/15715124.2014.885437
http://www.tandfonline.com

1999), or failure of often expensive bank protection works. Where the natural behaviour of the reach or system being managed is not properly understood, engineering failure is usually inevitable (Gilvear and Winterbottom 1992, Wyzga 1993, Marston *et al*. 1995, Petit *et al*. 1996, Surian 1999, Winterbottom 2000, Surian and Rinaldi 2003).

Accordingly, effective, holistic river management requires an improved understanding of sediment transfers within a catchment (Kondolf *et al*. 2002, Piégay *et al*. 2004, Liébault *et al*. 2008, Pont *et al*. 2009, Rinaldi *et al*. 2011). In gravel-bed rivers, bedload is the major determinant of channel morphology (Leopold 1992), thus changes in morphology reflect bedload flux, such that a direct link exists between coarse sediment transfer and channel morphology (Raven *et al*. 2010b, Fuller *et al*. 2011), which also directly impacts flood capacity and conveyance, as well as channel stability (cf. Fuller and Basher 2013). Repeat measurement of channel morphology, therefore, can be used as a tool to estimate coarse sediment transfers (Ashmore and Church 1998) and help underpin sustainable gravel management (Fuller and Basher 2013). This paper extends Fuller and Basher's (2013) work in the upper Motueka by addressing the wider, 'whole-catchment' issue of sediment conveyance to the coast through this river system. In this context, gravel management is important, but only part of the wider picture of sediment dynamics in the system (Liébault *et al*. 2008). Also of significance is suspended sediment which, while less crucial in terms of conditioning gross channel morphology and associated flood capacity and conveyance (Fuller and Basher 2013), has important implications relating to in-stream habitat quality, coastal sand replenishment and associated offshore water quality in connection with the coastal sediment plume from the Motueka river mouth (Fenemor *et al*. 2011). This paper, therefore, brings together our understanding of coarse sediment transfers in the upper Motueka with work on the suspended sediment budget of the whole Motueka to provide an improved scientific basis to underpin management of the Motueka River and its coastal plume. It is vital that those tasked with river basin management recognize the 'joined-up nature' of river works, both in terms of impacts and affects within a catchment, as well as beyond it and into the littoral zone. The effects of change within a catchment are well understood, e.g. Kondolf *et al*. (2002) usefully contrast channel response to land-use changes that have resulted in, respectively, sediment starvation leading to channel narrowing and incision; and over-supply of sediment prompting channel widening and aggradation. Nevertheless, very few river basin management studies go further than the catchment outlet, focusing on system dynamics and response to land-use change within catchments. However, in an effort to understand processes conditioning sediment transfers from catchment to coast there has been a recent focus on source to sink studies under the MARGINS programme, with integrated marine-terrestrial studies in the Waipaoa (Carter *et al*. 2010) and Fly Rivers (Goni *et al*. 2008), although this programme is not strictly management-focused. In this paper, we highlight the connections both within the Motueka and the adjacent coast with a management emphasis. Furthermore, by providing a more holistic understanding of systems such as the Motueka, which are grounded in data-rich investigation, we can help avoid resorting to hearsay and speculation that would otherwise result in unwise management decisions.

2 Catchment description

The Motueka catchment (2076 km^2) is located in the northern South Island of New Zealand (Figure 1). It drains into Tasman Bay and is a significant influence on both this bay and the adjacent Golden Bay, delivering large quantities of fresh water, sediment and nutrients to the littoral zone. The catchment is underlain by a diverse geology, including basement igneous, ultramafic and sedimentary rocks, as well as extensive clay-bound gravels (Moutere Gravels) (Basher 2003). Rainfall in the temperate maritime climate ranges from c. 950 mm in the east of the catchment to >3500 mm in the western ranges, and the mean flow of the river at Woodmans Bend (cf. Figure 1(a)) is 82 m^3 s^{-1} (Basher 2003). Sixty per cent of the catchment was cleared of native forest since Maori occupation (c.1350 AD) and European settlement in the 1800s (Fenemor *et al*. 2011). Approximately 40% of the catchment remains under native forest cover, 6% is native scrub, 5% native grassland, 27% plantation forest and 18% pastoral grassland and horticulture (Fenemor *et al*. 2011). Horticulture occupying the floodplain of the Motueka has required intervention in the river to protect this high-value land, as well as houses and infrastructure. The upper Motueka, with an average slope of 0.005 m/m, was naturally wandering, typically laterally active, locally divided and characterized by avulsions within the active channel and riparian zone, but this variability has been reduced and active channel width narrowed by c. 7% between 1960 and 2000 (Ball 2004). The lower river, with an average slope of 0.003 m/m, is single thread and more meandering, but also constrained by bedrock in some reaches (Basher 2003). River control works (fairway clearance and bank protection) were implemented in 12 km of the lower Motueka in 1954 and in 18 km of the upper Motueka in 1958. Complementing these river control measures were soil conservation farm plans and erosion control schemes, primarily for gully and streambank stabilization on Moutere gravel terrain (Basher 2003). Basher (2003) lists the major works initiated as part of the Motueka Catchment Control Scheme in 1982, including: stopbanks sited at strategic locations (settlements and bridges); establishment of clear channels of uniform width using a combination of river training, fairway clearance, bank protection (using rock, plant materials or a combination of both) and groynes; provision of vegetation screens along riverbanks to contain the spread of water and sediment from rivers during floods. Acute river bends have also been straightened. The major impact of river control has been to narrow and straighten the main channel (Basher

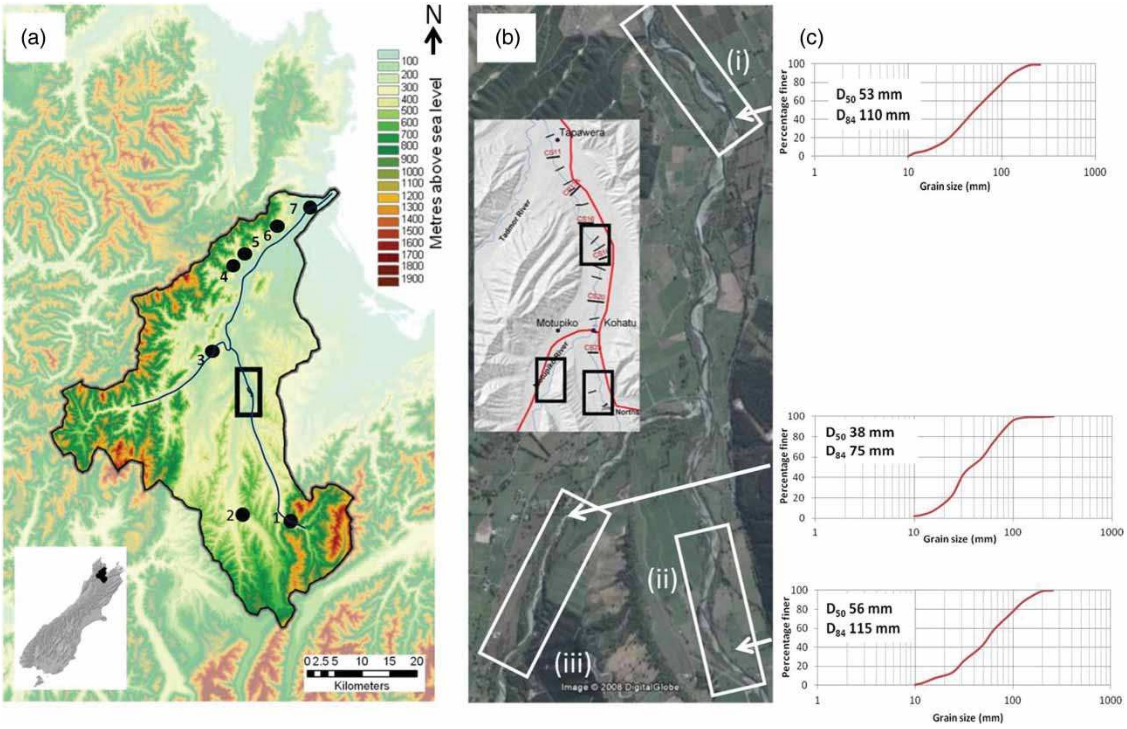

Figure 1 (a) Motueka catchment showing gauging sites referred to in the text: 1: Motueka at Gorge, 2: Motupiko at Christies; 3: Wangapeka at Walter Peak; 4: Little Pokororo; 5: Big Pokororo; 6: Herring and 7: Motueka at Woodman's Bend. (b) Location of sites used in assessment of bedload dynamics via DEM generation: (i) Three Beaches, (ii) Norths Bridge and (iii) Quinney's Bush. (C) Surface grain size data cumulative frequency curves for sites shown.

2003). This is in accord with the findings of many other studies on the impacts of river management in laterally active, gravel-bed rivers (Gilvear and Winterbottom 1992, Wyzga 1993, Surian 1999, Winterbottom 2000, Wishart *et al*. 2008). Gravel extraction has been used since the late 1950s to manage channel stability and flood conveyance capacity with up to c. 200,000 m^3 of gravel being removed annually. In the upper Motueka at Three Beaches (cf. Figure 1(b)), median grain size in the gravel armour layer is 53 mm, with a D_{84} of 110 mm (Figure 1(c)).

3 Suspended sediment

3.1 *Characterizing short- and long-term sediment yield and sediment sources*

Long-term (multi-decadal) average annual catchment specific suspended sediment yield (SSY) (t km^{-2} y^{-1}) and load (t) delivered to the coast were calculated using NIWA's Suspended Sediment Yield Estimator (SSYE, Hicks *et al*. 2011). The SSYE was developed by Hicks *et al*. (2003) to predict specific yields of suspended sediment at a national scale from mean annual rainfall and terrain characteristics (defined by an erosion terrain classification):

$$\mathrm{SSY} = aP^{1.7}$$

where SSY is the suspended sediment yield (t km^{-2} y^{-1}), P is mean annual rainfall (mm) and a isa constant depending on erosion terrain and reflects sediment availability.

A full description of this model is given in Hicks *et al*. (2011). It should be noted that the model only estimates the contribution of the suspended sediment load (clay, silt and fine sand) and there are no estimates of bedload (coarse sand and gravel). For erosion terrains with a significant presence in the catchment, the a values range over a factor of 11, from 8.3×10^{-5} for mountain formed in hard, coarse-grained igneous and metamorphic lithologies, through 4.1×10^{-4} for Pleistocene Terraces and fans, 5.8×10^{-4} for mountains formed in hard sedimentary lithologies, to 9.2×10^{-4} for hill country formed in soft conglomerate (Hicks *et al*. 2011). Based on the SSYE, the sediment load for the Motueka is 349,182 t y^{-1}, which equates to a specific SSY of 168 t km^{-2} y^{-1}, accounting for 41% of total load to Tasman and Golden Bays (Basher and Hicks 2012).

This SSYE estimate from the Motueka catchment was reasonably well validated by an independent data set collected as part of the Motueka Integrated Catchment Management (ICM) research programme (Fenemor *et al*. 2011). For this, during the period 2002–2008 seven sites were instrumented with flow gauges, turbidity sensors and automatic water samplers to monitor sediment yield within the catchment and delivered to Tasman Bay (Table 1, Figure 1(a)). The 7 years of 15-min records from the site at Woodmans Bend, near the coast, were used to develop a suspended sediment rating curve which was then used to estimate

Table 1 Summary of measured suspended sediment data for sites within the Motueka catchment. Measurement sites are located in Figure 1

	Motueka at Woodman's Bend	Motupiko at Christies[a]	Wangapeka at Walter Peak	Motueka at Gorge[a]	Little Pokororo	Big Pokororo	Herring
Period of record	23/11/02–30/06/08	18/11/02–30/06/08	19/11/02–30/06/08	6/04/04–30/06/08	1/07/06–30/6/08	1/07/06–30/6/08	1/07/06–30/6/08
Annual SSY (t km^{-2})[d]							
2003/2004	86	22	125				
2004/2005	79	539	27	2535	15	8	116
2005/2006	38	55	73	266	21	13	181
2006/2007	18	21	47	106			
20007/2008	73	113	210	138			
Mean SSY (t m^{-2} y^{-1})							
May 2004–June 2008	71	179	91	745			
July 2006–June 2008	45	67	128	122	18	11	152
Long-term SSY[a] (t km^{-2} y^{-1})	196[b] (136)	110[c] (110)	148[d] (137)	507[e] (533)			
% pine forest	27	30	4	<1	37	25	59
% indigenous forest, scrub and grassland	52	45	94	99	44	65	28
% pastoral grassland	17	23	1	<1	14	6	7
Average upstream slope (°)	20.7	16.4	29.5	26.5	23.7	24.7	20.0

Note: Herring catchment was being partially harvested during the measurement period: Little and Big Pokororo were the controls to establish the effects of harvesting. Monitoring was discontinued at all sites in June 2008.
[a]Based on discharge for entire flow record at each site; figures in brackets are for the common period at all sites (1990–2009).
[b]1969–2009.
[c]1990–2009.
[d]1981–2009.
[e]1965–2000.

annual and average loads since the commencement of flow records in 1969. This produced a mean annual yield of 401,800 t y^{-1} (198 t km^{-2} y^{-1}).

The ICM suspended sediment data set, which captured a large storm event in March 2005 with a >50-year Annual Recurrence Interval (ARI) in the Motueka headwaters (Hicks and Basher 2008, Basher *et al*. 2011), highlighted how variable SSYs are over time and across the catchment (Table 1). These varied by a factor of 25 at sites affected by the March 2005 flood (from 138 [2003/2004] to 2535 t km^{-2} [2004/2005] at the Motueka Gorge site), and at Woodmans Bend varied by a factor of 5 (18 [2006/2007]–86 t km^{-2} [2003/2004]). This is equivalent to variation in annual yield delivered to the coast ranging from 36,900 to 176,300 t. Long-term average sediment yields were estimated to range from 110 t km^{-2} y^{-1} for the Motupiko at Christies site to 507 t km^{-2} y^{-1} for the Motueka Gorge site. The annual load from the Motueka to the coast, derived from the sediment rating at Woodmans Bend, is highly variable and ranged from 49,000 t to 1.7 Mt (Figure 2 and cf. Basher *et al*. 2011). Sediment loads have been relatively low in the last two decades: during the period of ICM measurements the average load was only 150,000 t y^{-1}, compared with the long-term average load of 401,800 t y^{-1}. The years with highest sediment delivery to Tasman Bay were those with big catchment-wide floods and/or high numbers of floods (1983 and 1974).

3.2 *Storm events*

Most sediment transported to Tasman and Golden bays is carried in flood flows (Hicks and Basher 2008, Basher *et al*. 2011). For example, during the seven-year monitoring period in the Motueka catchment, 70% of the load measured at the Motueka Gorge and Motupiko sites was carried in a single flood event in March 2005. At all four sites measured in that study (Table 1), the five largest events carried between 58% and 89% of the total load measured over the whole monitoring period. The influence of discharge on flood sediment loads is illustrated for two sites in the Motueka (a headwaters site at Gorge and a near-coastal site at Woodmans Bend) in Figure 3(a), which shows a power law relationship between sediment load and peak discharge during flood events.

The March 2005 storm in the Motueka had a return period of >50 years and had a profound influence on sediment yield – Hicks and Basher (2008) describe it as a ‘threshold’ event and suggest that such effects occur for storms with a >20-year ARI. In the affected headwaters immediately following this event storm sediment yields increased by a factor of >10 (see Figure 3(b) for an illustration of the effect on event sediment yields) compared to storms of the same hydrological magnitude (i.e. peak discharge) that occurred before the March 2005 event. At the coast (Woodmans Bend site), storm yields increased by a factor of 2–3. Since the March 2005 event, sediment yields have slowly declined to pre-event levels over a period of several years.

3.3 *Sediment yields and land cover*

Both the SSYE model and our short-term measurements suggest most sediment is generated from areas of the catchment under forest and indigenous grassland because these areas are characterized by high rainfall, steep slopes and erodible rock types. Using the SSYE, Basher *et al*. (2011) estimated that the three largest sub-catchment contributors to total sediment load were the Motupiko (24.4% of the load from 16.3% of the catchment area), upper Motueka (16.9% of the load from 7.9% of the catchment area) and Wangapeka Rivers (10.2% of the load from 22.8% of the catchment area). In these three catchments, the proportions of forest (indigenous and pine forest) and indigenous grassland are 66%, 86% and 83%, respectively. Areas of the catchment underlain by erodible Separation Point Granite also have high specific sediment yield. The association between specific SSY, rainfall, geology, slope and land cover is illustrated in Figure 4.

However, in the lower rainfall areas of the catchment (cf. Figure 4), the effect of land use is significant. Hicks (1990) found that sediment yields were 20 times higher under pasture (78 t km^{-2} y^{-1}) than for mature pine forest (4 t km^{-2} y^{-1}) in small catchments underlain by Moutere gravel in the region. However, forest harvesting has a significant effect on sediment yield. Its magnitude depends on the area of trees harvested, the quality of road and landing construction, the inherent susceptibility of the terrain being harvested, and storminess during the post-harvest ‘window-of-vulnerability’ (Phillips *et al*. 2012). Basher *et al*. (2011) characterized the impact of forest harvesting in the Motueka catchment and compared it with the magnitude of storm influences on sediment yield. Forest harvesting elevated sediment yields (Table 1) producing a five-fold increase in event-specific SSYs (Figure 5), but they recovered to pre-harvesting levels within five years. The magnitude of the sediment yield increase, the time to recover and the total area affected were all smaller than the impact of large storms (see Basher *et al*. 2011). Impacts of forest harvesting on variation in sediment yield are probably minor because only a small proportion is harvested in any one year (assuming a 25-year harvest cycle, on average about 1% of the catchment would be harvested at any one time). Accordingly, it is unlikely that land use is a major influence on the patterns of variation of annual sediment load shown in Figure 2. The magnitude of these variations is so large (1.5 orders of magnitude) that it is far greater than the likely effect of land use, and they are probably largely due to variations in storminess and flooding. Basher *et al*. (2011) show that the timing of the highest annual sediment loads varies between sites in response to the timing of large floods or high numbers of flood events in the respective catchment areas.

This variability in annual sediment load is important to note, since land-use change is often used as a means of addressing elevated sediment loads by catchment managers and forestry is often perceived as the default option to reduce sediment load. However, these data indicate that natural storminess and

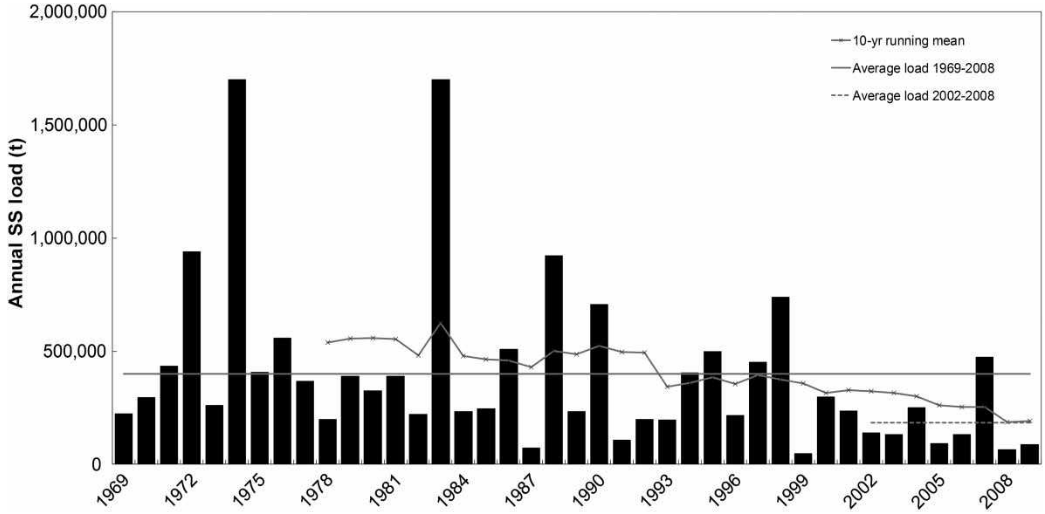

Figure 2 Variation in annual sediment load to Tasman Bay from the Motueka River. The dotted line shows the average load during the measurement period (2002–2008, 150,000 t y^{-1}) and the solid line shows the average sediment load from 1969 to 2008 (401,800 t y^{-1}).

underlying topography and lithology are in fact more significant drivers of the recent variability in annual sediment load in the Motueka system. This is important because it sets limits, in this catchment at least, on what can be achieved by land-use change in terms of anticipated reduction in fine sediment load, which also has implications for fisheries, both in the river and the littoral zone affected by the Motueka sediment plume, which we discuss below.

4 Fine sediment and fishery issues

Fine sediment has been suggested as causing declines in both the trout fishery in the river and the scallop fishery in Tasman Bay (see Jellyman *et al*. 2003, Young 2003, Handley 2006, Gillespie *et al*. 2011). The river is widely recognized for the quality of its brown trout fishery, but in the mid-1990s trout numbers declined dramatically and remained low for almost a decade (Figure 6). The effect of sediment in the river has been implicated in this decline (Jellyman *et al*. 2003, Young 2003). However, through most of the river there is a very low proportion of fine sediment on the river bed (Figure 7(a)) and changes in response to major storm events such as the March 2005 flood are small and of short duration (Basher unpublished data, cf. Figure 7(b)). Furthermore, the decline in the trout fishery has occurred at a time when the sediment load carried by the river has tended to be relatively low (Figure 2). Major factors affecting trout abundance have been identified as flooding, food abundance, water temperatures and low flows (Young personal communication, 2010). The effect of high flows during and shortly after the critical period when fry emerge from the river bed was highly significant as has been well documented in previous studies (Hayes 1995, Jowett 1995). These results suggest variation in trout numbers has little relationship with sediment abundance or land use, despite the perception of anglers (Jellyman *et al*. 2003) and that trout numbers will likely show cyclical variation in response to trends in hydrology and food abundance.

Scallop numbers in Tasman Bay have exhibited similar trends to the trout fishery with a significant decline since the mid-1990s (Handley 2006), following an earlier decline in the early 1980s (Figure 8). Anecdotally, it has been argued that land use including the effects of sediment generated by forest harvesting and deforestation is a key driver for the trend in scallop numbers. However, Basher and Hicks (2012) suggest that the fishery has declined at a time when sediment yields to Tasman Bay have been relatively low and that the influence of sediment is more likely to be a cumulative effect relating to accelerated rates of sedimentation on the sea floor since deforestation rather than a direct effect of current land use. It does appear that the sedimentary structure of the sea floor has changed significantly but there is debate about whether this is an effect of accelerated sedimentation from land-based sources or disturbance of the sea floor by dredging and bottom trawling causing re-suspension of deposited sediment (Handley 2006).

5 Managing gravel

Gravel extraction is a key issue in the Motueka River. The relevant local authority, Tasman District Council, has progressively reduced the extraction limit from the upper Motueka (cf. Figure 9(a)). Currently the Proposed Tasman Resource Management Plan sets annual average allocations of 3000 m^3 for the upper Motueka and 2000 m^3 for the Motupiko River. These decisions were based largely on cross-section derived assessments of mean bed level (MBL). The progressive reduction in MBL over time at most sections (Figure 9(b)) results in a decline in gravel volume stored in the channel (channel storage loss), which is at least in part attributed to gravel extraction (Figure 9(c)). Channel storage changes were calculated from the product of change in MBL, channel width and distance

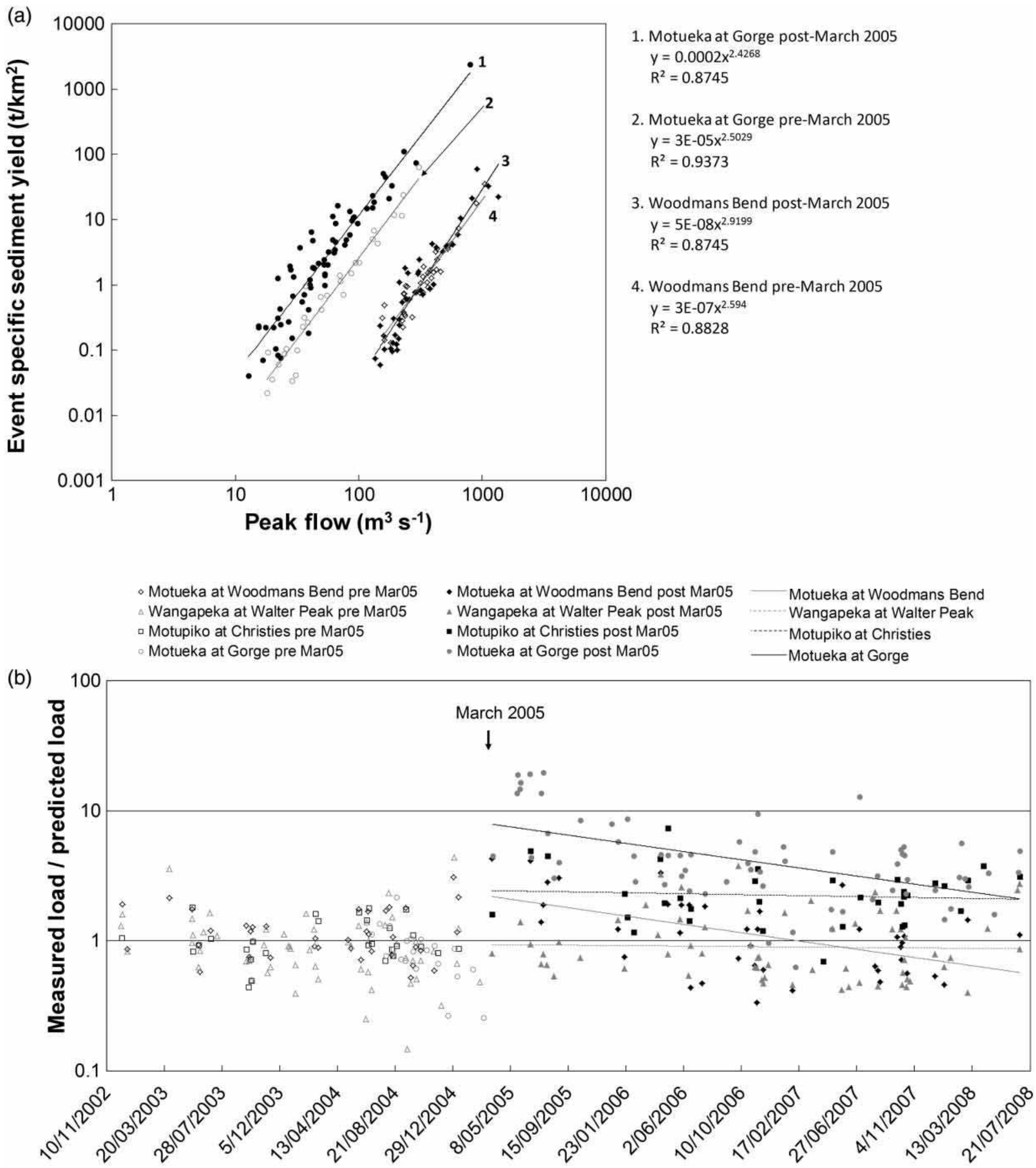

Figure 3 (a) Relationship between storm event-specific SSY and event peak discharge for headwater (Motueka at Gorge) and near-coastal (Motueka at Woodmans Bend) sites. This also shows the profound effect of the March 2005 storm at the Gorge site, and the smaller effect at Woodmans Bend. (b) Trend in ratio of predicted specific SSY to measured SSY at primary sites. Best-fit regression lines for the temporal trend in predicted SSY are shown for the post-March 2005 data.

between cross sections. The observed trends may suggest an under-supply of sediment, relative to transport capacity within the Motueka system in recent times. It is likely that the degradational trends identified in Figure 9(c) is long term (at least multi-decadal), since coasts in the region are also eroding (Gibb 1978, Mueller 1990), suggesting a reduction in sediment supplied to them by rivers, thus the behaviour of the discrete reaches being assessed here must be understood in this wider catchment context.

Setting allocation limits for gravel extraction from the rivers of Tasman District is a highly contentious issue because of generally low gravel supply compared with many other areas of New Zealand (Basher 2006). Over-extraction can lead to undesirable effects on bed degradation, channel stability and groundwater levels (Wishart *et al*. 2008). Defining sustainable gravel extraction volumes requires an understanding of bed-level dynamics and sediment transfers which have traditionally been derived from periodic (every four to five years) river cross-section surveys (Sriboonlue and Basher 2003, Basher 2006), but such surveys may underestimate sediment transfer volumes (Vale and Fuller 2009) and do not necessarily effectively encompass channel dynamics (Fuller *et al*. 2003).

Riverbed digital elevation models (DEMs) have been used in an attempt to more rigorously quantify annual sediment transfers between 2004 and 2010 using a DEM differencing approach described by Fuller and Basher (2013). Reaches in the upper

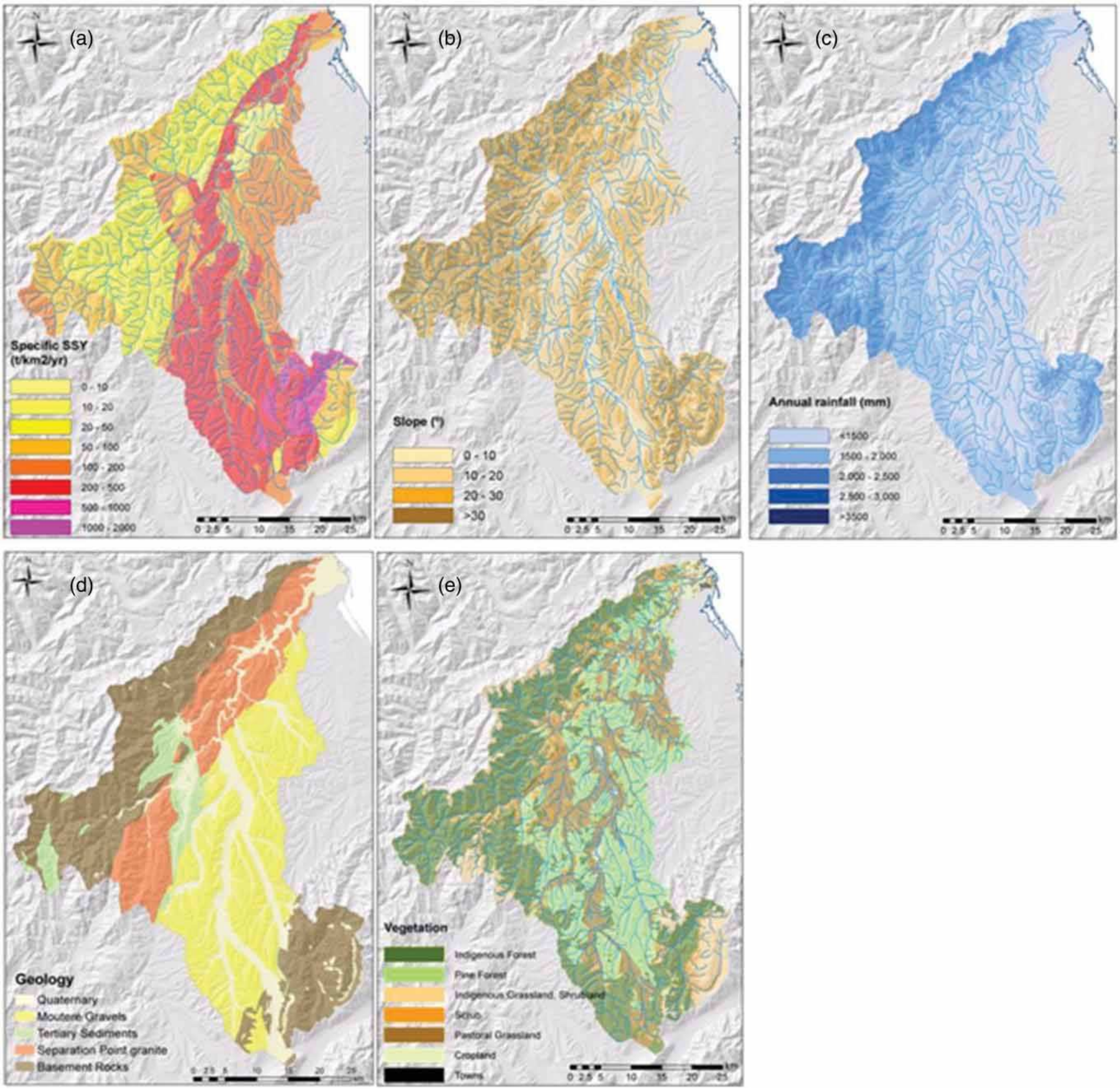

Figure 4 Motueka catchment: (a) Spatial distribution of specific SSY; (b) slope classes; (c) annual rainfall distribution; (d) geology and (e) vegetation distribution.

Motueka River (Figure 1(b)) were mapped annually between 2004 and 2010 using Real Time Kinematic-differential Global Positioning Survey and Total Station ground survey equipment to generate channel topography data for DEM construction. DEMs were generated in Surfer® spatial analysis software using Triangulation with Linear Interpolation. Successive DEMs were subtracted from one another to create a DEM of difference, producing a surface representing the distribution of change between surveys from which volumetric change was derived. Full details are available in Fuller and Basher (2013). The results (DEMs of difference and associated sediment transfers) are given in Figure 10 and Table 2 and discussed at length by Fuller and Basher (2013).

There is clearly a considerable degree of variability in sediment transfers on a year-to-year basis (cf. Figure 10 and Table 2), which partly reflects the magnitude and frequency of bedload-transporting flows in these reaches (cf. Figure 10(d) and 10(e)), but probably also reflects variation in upstream sediment supply. Higher flows transport more material (cf. Fuller and Basher 2013 for more detailed discussion of flow competence and relationship with sediment transfers). This variability may also reflect the passage of bedwaves through these reaches, which would increase sediment transfers. However, there is no clear evidence of this, which probably reflects the frequency of surveys and length of record. While the precise cause of the changes observed may remain speculative (likely a combination of flows and bedwaves); importantly, these results demonstrate that within straightened, narrowed reaches of a wandering gravel-bed river, the system remains dynamic and challenges the concepts based on stable channel design that has provided the rationale for the narrowing and straightening of the Motueka active channel (cf. Raven *et al*. 2010a). This reaffirms the default characteristic of such systems as unstable (Raven *et al*. 2010a) and emphasizes the need for effective management to 'work with

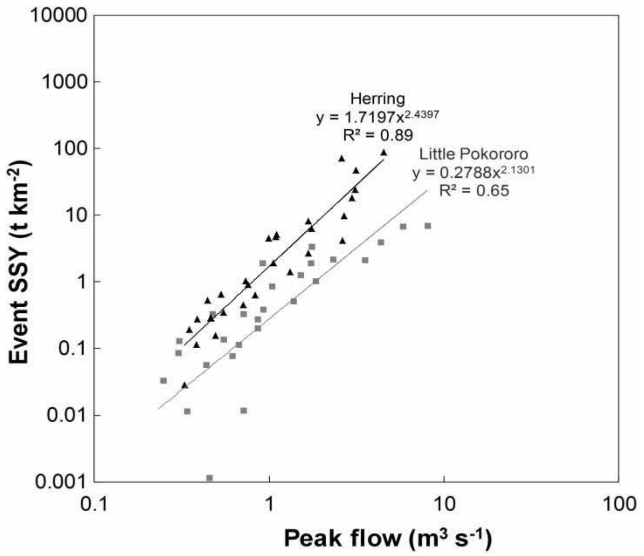

Figure 5 Relationship between storm event-specific SSY and event peak discharge for control (Little Pokororo) and harvested catchment (Herring).

nature', rather than 'fight the site' (Brierley and Fryirs 2009). Furthermore, what is also of significance is an overall degradational trend in the mainstem Motueka reaches over the timescale of these surveys, combined with a high degree of morphologic change within the narrowed active channel, which is also observed in similar systems (Gilvear and Winterbottom 1992, Wyzga 1993, Marston *et al*. 1995, Petit *et al*. 1996, Surian 1999, Winterbottom 2000, Surian and Rinaldi 2003, Wishart *et al*. 2008). Laterally, constraining the channel enables excess stream power to scour its bed, deepening the channel and resulting in degradation. As the channel deepens, higher flows become confined within channel and given armoured banks, further scour is inevitable – at least until this is limited by development of a stable bed armour. Such incision decouples channel and floodplain processes and disconnects large areas of a catchment from the sediment cascade (Fryirs *et al*. 2007). In containing larger floods and concentrating flows, incised channels potentially generate higher transport capacities, resulting in the mobilization of large volumes of bedload and further bed degradation (Fryirs and Brierley 2001). This gives the appearance to the casual observer of the reverse effect, whereby gravel bars (beaches) become more prominent within the active channel as the wetted channel deepens, and pressure is often exerted by adjacent landowners to extract gravel to remove the apparent (but in fact non-existent) build up, which in turn exacerbates the apparent trend. Until good-quality data are provided, speculation about bed-level trends can accordingly result in complete mismanagement of the river.

DEM results also suggest that the upper Motueka river bed is degrading at a slow rate (it has degraded on average c. 0.3 m since the 1960s, cf. Figure 9(b), and 9(c)), and this has been the basis of restrictions on gravel extraction. Again, we need to be cautious about how much gravel we extract, since the impact of extraction diffuses upstream and downstream, lowering the bed, but to improve our ability to properly manage the resource we need to know more about how much gravel is moving through these river systems and what proportion we can extract without having effects that we deem undesirable (on costs of river control and groundwater levels). More research, and less speculation, is needed into the relationship between bed-level trends in the upper and lower reaches of the Motueka River, as well as erosional trends at the coast to better understand the relationship between bed levels, sediment supply, gravel extraction, degradation and erosion. Gravel management in the

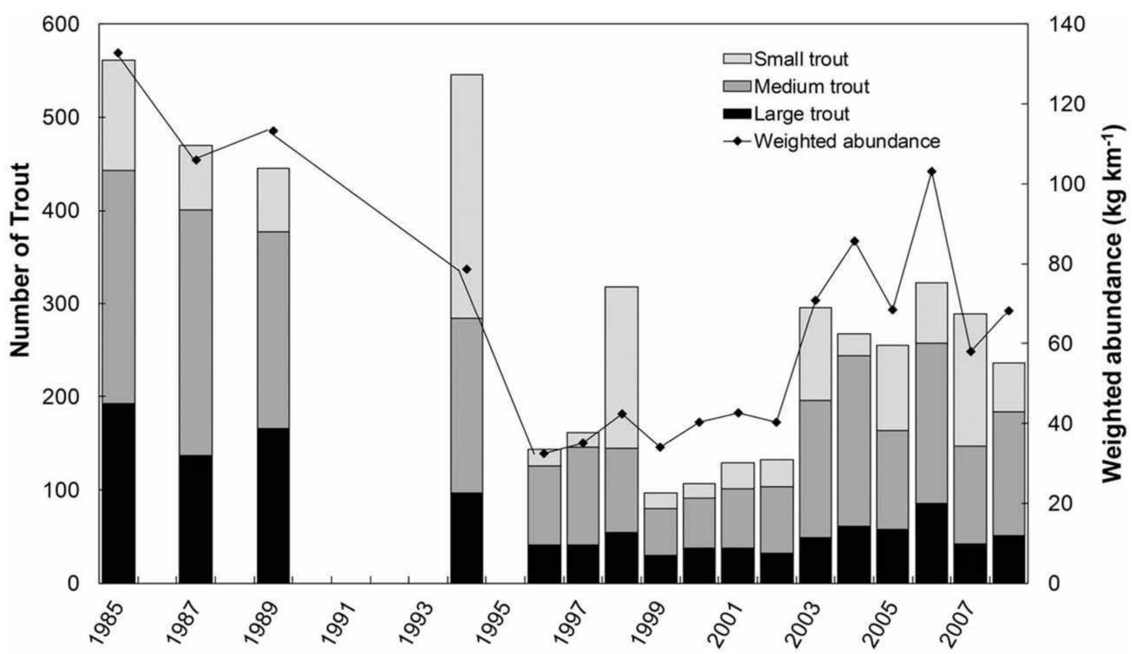

Figure 6 Trends in trout numbers and abundance measured by drift dives at Motueka at Woodstock since 1985 (data courtesy of Nelson-Marlborough Fish & Game).

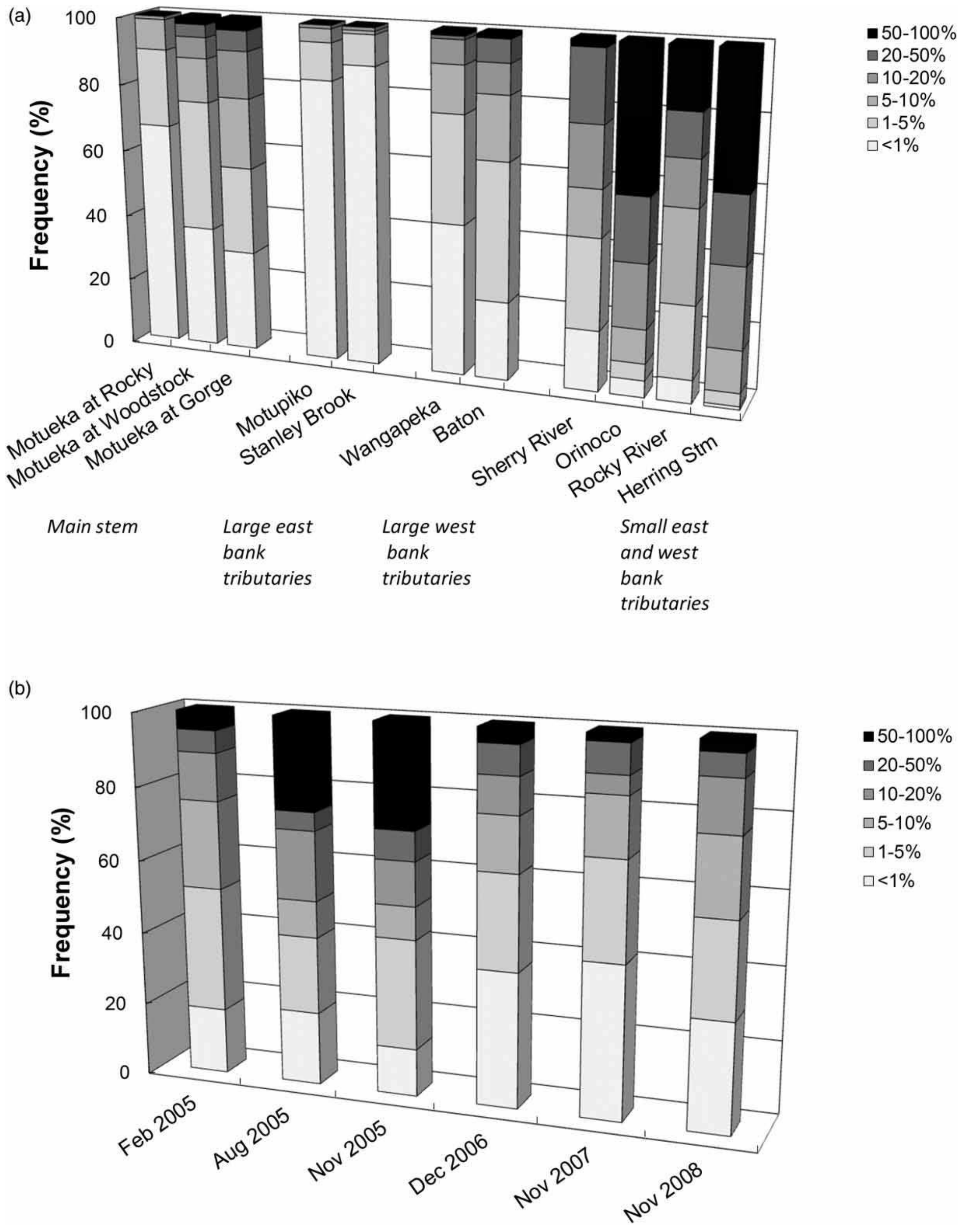

Figure 7 (a) Fine sediment abundance at selected sites in the Motueka River. Based on proportion of fine sediment (<2 mm diameter) recorded at 100 points in each river reach. (b) Changes in fine sediment abundance at Motueka at Gorge site from March 2005 to November 2008.

Motueka, therefore, needs a cautious, adaptive management approach, with better information on gravel transport rates and better approaches to defining the proportion that can be sustainably harvested. The degradational trends in the upper Motueka are also characteristic of the lower Motueka: Sriboonlue and Basher (2003) found that the lower Motueka cross sections were also degrading (Figure 11). This indicates that the sediment scoured from the upper river is not simply redeposited further downstream, but appears to be contributing to an overall loss of bedload material in the river as a whole.

6 Discussion

An extended suspended sediment data set for the whole Motueka catchment and more local annual morphological budgets characterizing bedload trends from reaches in the upper Motueka appear to indicate an overall reduction in sediment load in this river basin, with commensurate effects on its adjacent coastal zone. However, it should be noted that suspended sediment trends are based on a sediment-discharge rating, rather than continuous measurement of suspended sediment, thus to some extent

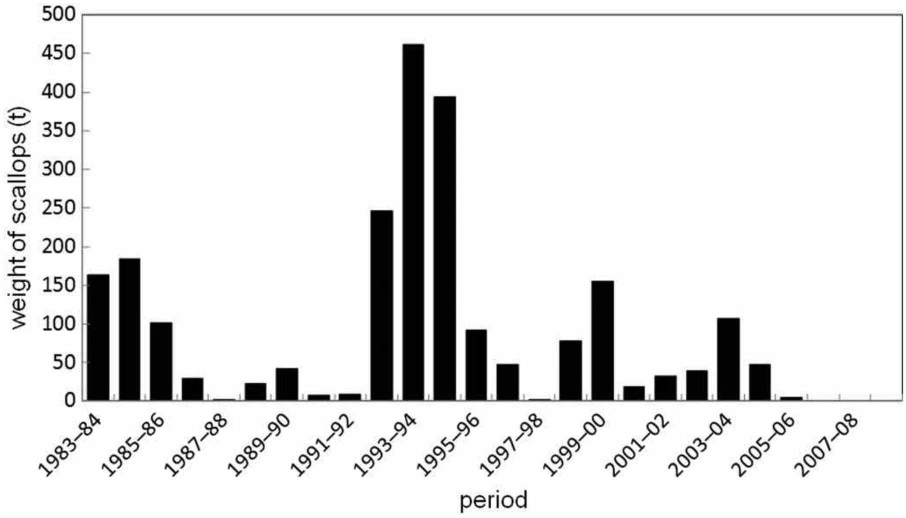

Figure 8 Weight of scallops landed from Tasman Bay 1983–2009.

reduced suspended load could be attributed to reduced flow. Nevertheless, an overall reduction in load would be consistent with a sediment exhaustion response to over-supply following European deforestation in the catchment in the 1800s. An analagous response has been observed in the European Alps, where channelization, catchment erosion control and re-afforestation over the last c. 100 years has reduced sediment loads, promoting channel narrowing and incision (Kondolf *et al*. 2002, Surian and Rinaldi 2003, Piégay *et al*. 2004, Liébault *et al*. 2008, Pont *et al*. 2009). Furthermore, comparison between paired catchments in New Zealand and the French preAlps by Liébault *et al*. (2005) highlights the effectiveness and response of river channels to afforestation programmes initiated since 1860 in France, which is about the same time that European-initiated clearance began throughout much of New Zealand. Beatson and Whelan (1993) record anecdotal evidence of severe flooding and sedimentation soon after European settlement of New Zealand. They suggest that widespread deforestation in the Motueka catchment in the 1870s was followed by severe flooding, accompanied by substantial erosion, which is precisely the situation recorded in the European Alps prior to afforestation (Surian and Rinaldi 2003). The Motueka River (and Tasman Bay coast) is now responding to the new sediment supply regime in the catchment. River control works, which have narrowed the river channel, exacerbate this riverbed degradation by confining flows and decoupling the channel and floodplain, reducing the possibility of replenishment from lateral reworking of floodplain material. In turn, because sediment supply from the catchment is diminished/diminishing, the natural tendency for the river to degrade its bed is enhanced and bank protection structures (rip-rap) are undermined. Further research is needed to establish whether a bed pavement (enhanced armouring) develops in response to this degradation, which might retard degradation rates. Bed degradation also decouples the higher bar platforms from replenishment, which have traditionally been relied upon for gravel mining and reducing the gravel resource in the channel. Similar river trajectories in Europe (Ziliani and Surian 2012) have led to deliberate attempts to replenish sediment in degrading reaches (Pont *et al*. 2009).

The Motupiko at Quinney's Bush, however, was predominantly aggradational during the period of survey (Figure 10 and Table 2). However, the fact that there was alternation at times between net deposition and net erosion suggests that superimposed upon any long-term trends are elevation and morphological changes that occur in response to the passage of discrete waves of bed material being transported through the reaches. Direct monitoring of bedload transport would allow this question to be addressed further and longer term monitoring would place the short-term trends identified here in a better context. This may be particularly significant in the light of the as yet undetermined impacts of the March 2005 Good Friday flood on bedload. It is possible that the effects of this event are yet to impact upon the studied reaches in the upper Motueka, although if following the suspended sediment trends, it is likely that any effects will be short-lived and only temporarily disrupt bed degradation trends evident at these sites. It is of interest though that the bed material size in the Motupiko is significantly finer than the Motueka at Norths Bridge (D_{50} 38 mm, compared with 56 mm, cf. Figure 1(c)), which may be consistent with the passage of a bedwave set off by the Good Friday event, as observed in the Motueka gorge on the mainstem, although no pre-event grain size data are available. Such features diffuse with distance and time and may become undetectable.

It must be noted that in both the suspended sediment and bedload data sets presented here there is a considerable degree of variability year to year, which makes it difficult to precisely link these trends with definitive causes. Indeed, Ziliani and Surian (2012) argue that short-term trends cannot be used to make inferences about longer term catchment-scale sediment supply. Furthermore, while overall the Motueka catchment may be recovering from the initial perturbation of clearance in the 1800s, more recent large-scale afforestation from the

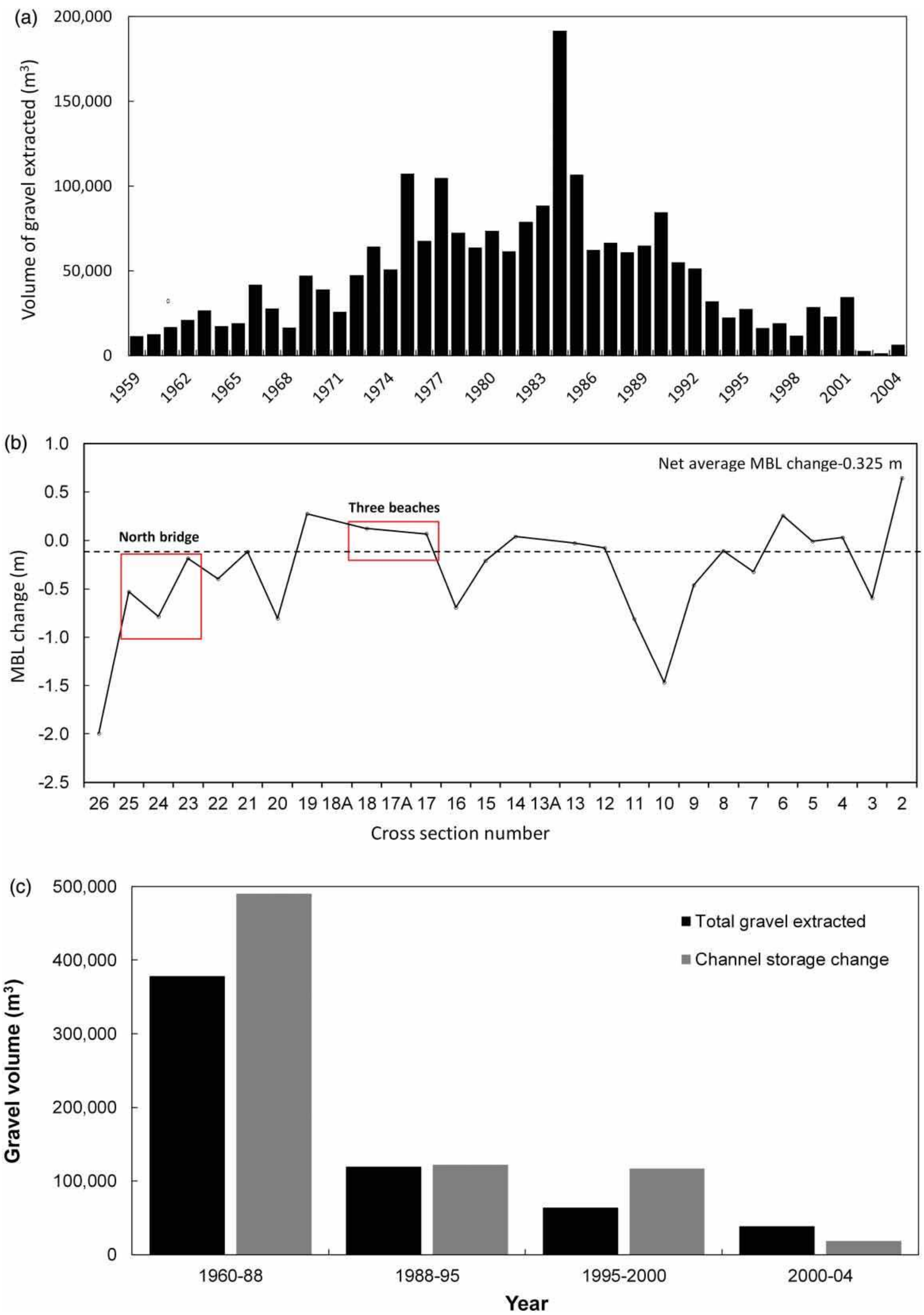

Figure 9 (a) Volume of gravel extracted from Motueka River 1959–2004 (data courtesy of Tasman district council). (b) Upper Motueka MBL change between 1960 and 2004 (Ball 2004). (c) Upper Motueka gravel volume loss between 1960 and 2000 (Ball 2004).

1930s–1970s would also make a significant, but unquantified contribution to reduction in sediment in the Motueka system, as is evident elsewhere (Kondolf *et al*. 2002, Piégay *et al*. 2004, Liébault *et al*. 2005, Pont *et al*. 2009). There may also be a response to climatic drivers such as the El Nino Southern Oscillation, which are known to affect flood frequency and erosion elsewhere in New Zealand at a decadal scale (Jenkins 2010), as well as a centennial scale (Richardson *et al*. 2013).

6.1 *Influence of sediment from the Motueka River on the coastal environment*

Declining sediment yields are most likely responsible for erosion of the Tasman Bay coastline reported by Gibb (1978) and Mueller (1990), especially since Handley (2006) discounts coastal erosion as a significant source of sediment into the Bay, although this may be disputed. Gravel is transported to the coast, but primarily deposited in the tidal and sub-tidal area

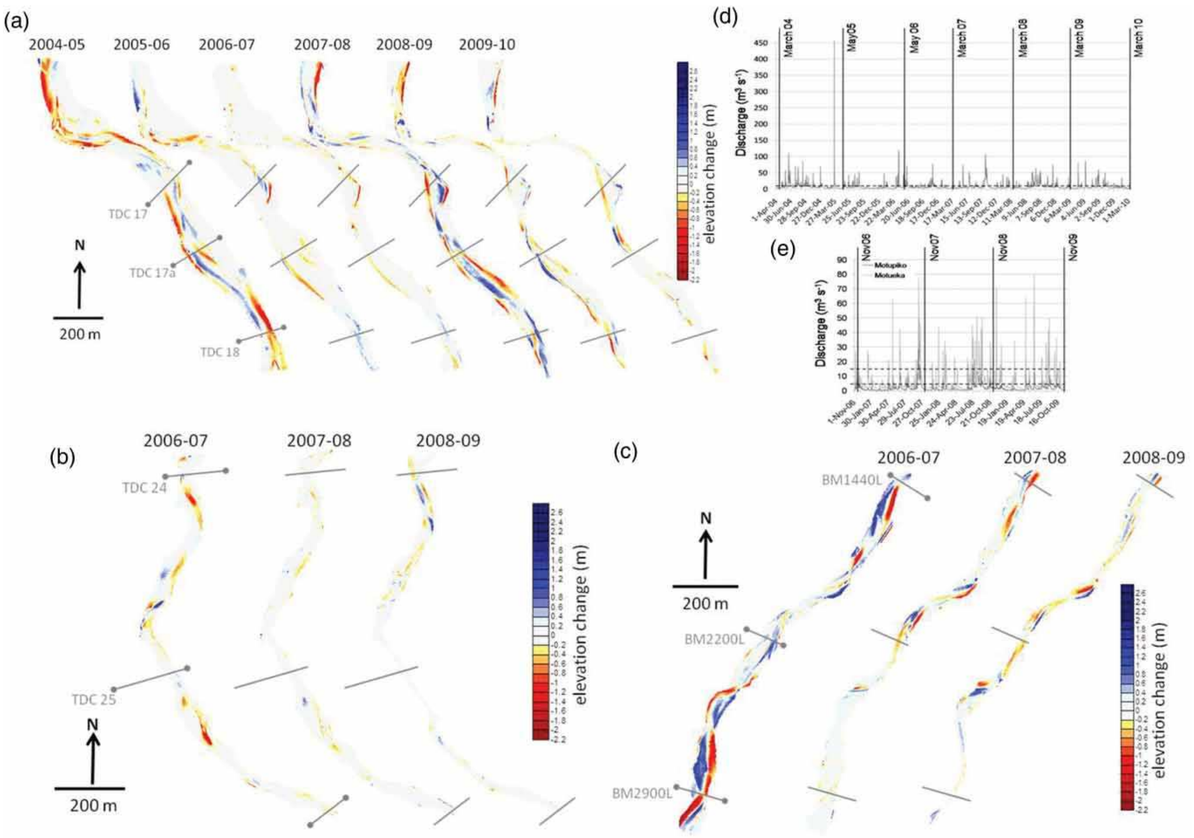

Figure 10 (a) DEMs of difference, three Beaches, 2004–2010; (b) Norths Bridge, 2006–2009; (c) Quinney's Bush, 2006–2009; (d) Motueka daily mean flow at Three Beaches (Motueka Gorge and Christies gauges combined) and (e) Motueka Norths Bridge (gauged Motueka Gorge) and Motupiko (gauged Christies) daily mean flows. Dashed lines indicate Q_{crit} values (cf. Fuller and Basher 2013), in (e) the upper line is associated with the Norths Bridge site (Motueka), the lower with Quinneys Bush (Motupiko).

Table 2 Sediment transfers at sites in the upper Motueka derived from DEM differencing (cf. Figure 10 and Fuller and Basher 2013)

Three Beaches			
Date	Erosion (m^3)	Deposition (m^3)	Net (m^3)
March 2004–May 2005	27,765	16,418	−11,347
May 2005–2006	9832	9043	−789
May 2006–March 2007	7063	5573	−1490
March 2007–2008	14,331	21,945	+7614
March 2008–2009	10,940	7721	−3219
March 2009–2010	7640	6800	−840
March 2004–2010	30,377	20,052	−10,325
Norths Bridge			
Date	Erosion (m^3)	Deposition (m^3)	Net (m^3)
Nov 2006–2007	8104	4836	−3268
Nov 2007–2008	4836	2901	−1935
Nov 2008–2009	3822	4245	+423
Nov 2006–2009	9677	5281	−4396
Quinney's Bush			
Date	Erosion (m^3)	Deposition (m^3)	Net (m^3)
Nov 2006–2007	16,427	23,084	+6657
Nov 2007–2008	7564	6361	−1203
Nov 2008–2009	5796	6986	+1190
Nov 2006–2009	9631	11,958	+2327

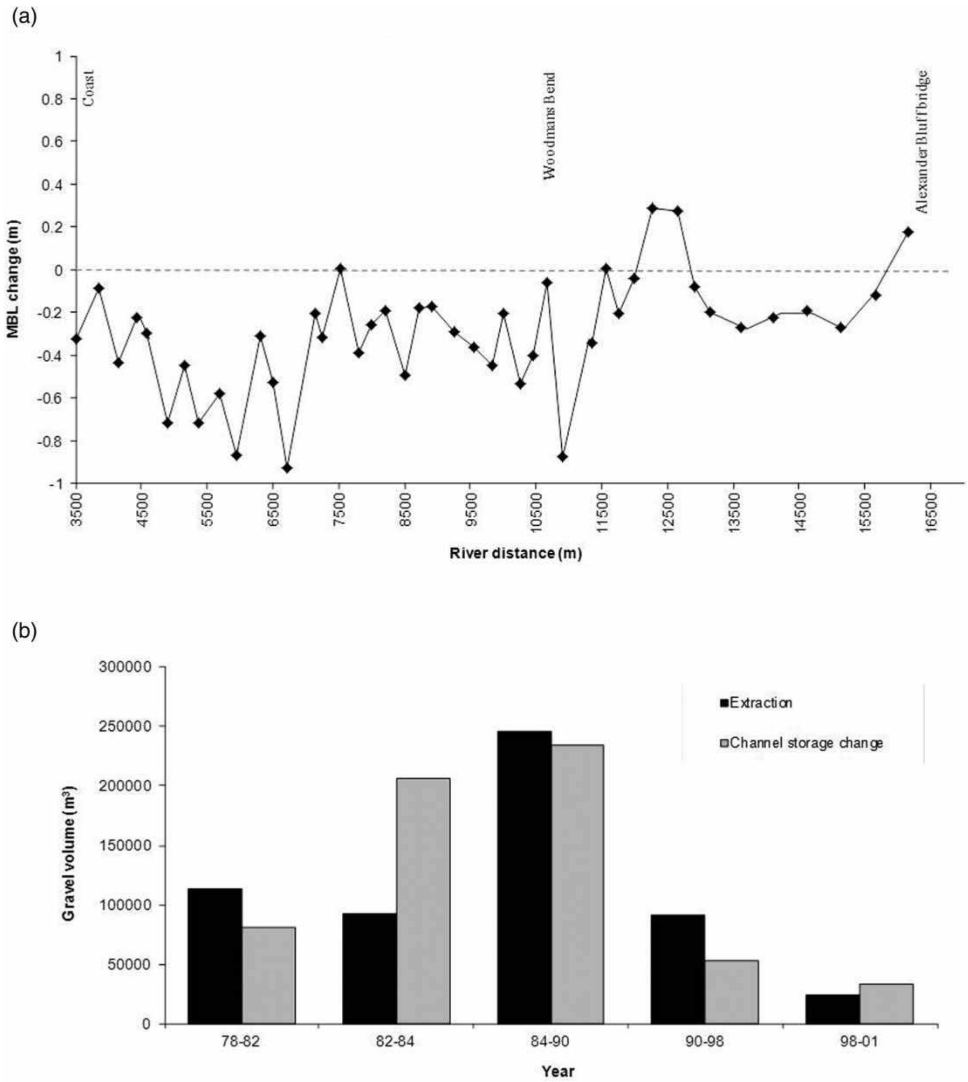

Figure 11 (a) Lower Motueka MBL change between 1978 and 2001 (Sriboonlue and Basher 2003) and (b) Lower Motueka gravel volume loss between 1978 and 2001 (Sriboonlue and Basher 2003).

adjacent to the coast in the vicinity of the river mouth (Mitchell 1987). However, much more work is needed to make the linkages between the river and coast clearer, which should include a longer term assessment of erosion over recent decades, analysis of sediment deposited at the river mouth and further out in the littoral zone.

While the sediment load of the river may have reduced over recent decades for various reasons, there is no obvious mechanism to link this with a decline in scallop fishery. The more likely explanation for such a decline is probably to be found offshore. Accordingly, any effect of the river is indirect, perhaps through re-suspension of deposited sediment that has accumulated since deforestation combined with changes to the sedimentary structure of the sea floor induced by trawling and dredging, rather than a direct result of land-use influences on sediment generation in the catchment.

6.2 *Future river management*

This paper sets out to improve understanding of sediment dynamics in the Motueka River to underpin management of the river and its coastal plume. As with many rivers responding to land-use change in the European Alps, the variability and trends in bedload and suspended load in recent decades indicate considerable complexity, which reflect an array of contributing variables that are both natural (e.g. storms) and anthropogenic (e.g. channel confinement). In turn, to provide a more rigorous scientific basis for management, and reduce speculation and mismanagement, requires better, longer, data sets. The results reported in this paper are limited in the sense that the long-term suspended sediment data are derived from sediment-discharge ratings, rather than from direct measurement of suspended sediment; and bedload dynamics are derived from very short-term studies in one part of the catchment. There remains a need to generate a more extensive data set to attempt to unravel some of the complexities inherent in the sediment dynamics of this system highlighted in this paper, both in suspended and bedload movement and trends.

If the premise of a declining sediment load were to be accepted, how should the river be managed? Clearly, the gravel resource appears to be diminishing, at least from the upper river, and ongoing extraction will only serve to further enhance channel degradation. While there may not yet be destructive consequences of this degradation to date, progressively lower bed levels will eventually lead that way. In order to mitigate channel degradation in the upper Motueka, channel–floodplain connections should be restored and, during degradational phases such as the present phase identified, gravel extraction reduced, which is how degraded alpine rivers in Europe have been tackled (Kondolf *et al*. 2002, Liébault *et al*. 2008, Pont *et al*. 2009). It appears that sediment supply from tributaries such as the Motupiko is insufficient to mitigate degradation alone (Fuller and Basher 2013). Increasing the fairway width and allowing the channel to migrate more freely would enhance channel–floodplain connectivity, replenish sediment and enable the river system to adjust more naturally to disturbance events such as storms. Management of similar rivers elsewhere has adopted just such an 'erodible corridor' approach to improve geomorphic and vegetation diversity (Piégay *et al*. 2005). There is clearly a need to recognize the dynamism inherent in constrained or controlled wandering gravel-bed rivers to manage such systems effectively. Brierley and Fryirs (2009) argue that geomorphic diversity should be respected in regard to rehabilitating or effectively managing rivers as a whole. This research in the Motueka has demonstrated considerable diversity in the behaviour of adjacent reaches in the same geomorphic compartments of a catchment, underlining the need to tailor management approaches at a reach-specific level. To do this effectively requires a clearer understanding of reach dynamics, morphological change and sediment transfers. Furthermore, these dynamics must be understood if management is to 'work with nature'. Therefore, we entirely agree with Brierley and Fryirs (2009, p. 1213), that it is 'imperative to frame management actions in relation to the character and behaviour of any given reach'. This must also be set within a context of understanding sediment dynamics in the catchment as a whole. Decline in SSYs from the catchment may reflect sediment exhaustion following disturbance, flooding and erosion in the 1800s. It is possible, although not yet proven, that bedload is likely to follow similar trends for the same reason.

The high degree of variability demonstrated in the suspended sediment data emphasizes the need to work with long-term data sets to properly understand patterns and controls of sediment transfers in this system. Identifying these longer term trends helps predict potential future trajectories. Any reduction trend in suspended sediment loads will likely be temporarily overridden by major storms (such as the Easter 2005 storm). This will have an impact offshore, and coastal management can be informed of such trends and strategies put in place to mitigate or accommodate coastline erosion. Elsewhere in many parts of New Zealand the key issue is reduction in SSY. It could be argued that land-use practice in the Motueka is beginning to return the sediment yield towards more natural (pre-settlement) levels, or it may simply reflect a period of smaller flows, but to ascertain this requires better understanding of longer term hydrological trends.

7 Conclusions

Inevitably there is a high degree of natural variability in transfer of both fine (suspended) and coarse (bed) sediment through a river system. Both suspended sediment data and annual morphological budgets from three selected reaches in the upper Motueka reflect this and the complexity inherent in this system. Accordingly, it is difficult to be precise when predicting sediment trends in such a natural, open system and more data are required before the causes and effects can be more thoroughly understood. Nevertheless, river management must take into account the inherent variability and dynamism if it is to be effective. Furthermore, the need for more high-quality data to underpin our understanding of system dynamics must be recognized, so that river management becomes more reliant on robust evidence and less dependent on speculation. Linkages between river and coast are also evident, if not clear, which means that coastal planners must also look upstream for answers to their problems. Similarly successful, integrated river management must also look off (or along) shore, as the ultimate destination for material transferred along the jerky conveyor that is the Motueka fluvial sediment system. Finally, the current sediment trends in the Motueka reflect to some degree the recent historical legacy in the catchment. It is imperative to recognize and understand that each catchment has a history, which conditions its behaviour and the potential for recovery (Brierley and Fryirs 2005). Arguably, the Motueka is now recovering from catastrophic disturbance in the 1800s associated with large-scale deforestation, but it remains a dynamic system, sensitive to disturbance by natural events and must be managed carefully. Continued confinement will restrict replenishment of the gravel resource and perpetuate channel degradation.

Acknowledgements

The following Massey University students assisted with fieldwork and data analysis in the Motueka: Jane Richardson, Rob Dykes and Simon Vale. Field assistance was also provided by David Feek, Erin Hutchinson, Alastair Clement, Emma Phillips, Arved Schwendel (Massey), Christine Daly, George Knights, Stephanie Merrill, Maria Borlinghaus, Diarmuid Neilan and Claire Butty (Landcare Internships) and Brenda Rosser (Landcare Research).

Funding

This work was funded as part of the Motueka Integrated Catchment Management Programme by the Foundation for Research, Science and Technology under contract C09X0305. We thank the Tasman District Council for providing the long-term cross-section data.

References

Ashmore, P. and Church, M., 1998. Sediment transport and river morphology: a paradigm for study. *In*: P. Klingeman, *et al.*, eds. *Gravel-bed rivers in the environment*. Highlands Ranch, CO: Water Resources Publications LLC, 115–148.

Ball, L., 2004. *Quantifying the morphological effects of gravel extraction on the Motueka River*. Unpublished masters thesis. Lincoln University, 78pp.

Basher, L.R., 2003. *The Motueka and Riwaka catchments: a technical report summarising the present state of knowledge of the catchments, management issues and research needs for integrated catchment management*. Lincoln: Landcare Research.

Basher, L.R., 2006. *Monitoring of riverbed stability and morphology by regional councils in New Zealand: application to gravel extraction management*. Landcare Research Contract Report, LC0506/138. Nelson: Landcare Research.

Basher, L.R. and Hicks, D.M., 2012. *Sediment generation and delivery to Tasman and Golden Bays*. Landcare Research Contract Report, LC997. Nelson: Landcare Research.

Basher, L.R., *et al.*, 2011. Sediment yield responses to forest harvesting and large storm events, Motueka River, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 45, 333–356.

Beatson, K. and Whelan, H., 1993. *The river flows on – Ngatimoti through flood and fortune*. Nelson: Kath Beatson & Helen Whelan.

Brierley, G.J. and Fryirs, K.A., 2000. River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environmental Management*, 25, 661–679.

Brierley, G.J. and Fryirs, K.A., 2005. *Geomorphology and river management: applications of the river styles framework*. Oxford: Blackwell Publishing.

Brierley, G.J. and Fryirs, K.A., 2009. Don't fight the site: three geomorphic considerations in catchment-scale river rehabilitation planning. *Environmental Management*, 43, 1201–1218.

Carter, L., Orpin, A.R., and Kuehl, S.A., 2010. From mountain source to ocean sink – the passage of sediment across an active margin, Waipaoa Sedimentary System, New Zealand. *Marine Geology*, 270, 1–10.

Davies, T.R.H., 1997. Long-term management of facilities on an active alluvial fan – Waiho river fan, Westland, New Zealand. *Journal of Hydrology (NZ)*, 36, 127–145.

Edwards, P.J., *et al.*, 1999. A conceptual model of vegetation dynamics on gravel bars of a large Alpine river. *Wetlands Ecology and Management*, 7, 141–153.

Fenemor, A., *et al.*, 2011. Integrated catchment management—interweaving social process and science knowledge. *New Zealand Journal of Marine and Freshwater Research*, 45, 313–331.

Fryirs, K.A. and Brierley, G.J., 2001. Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. *Geomorphology*, 38, 237–265.

Fryirs, K.A., *et al.*, 2007. Buffers, barriers and blankets: the (dis)-connectivity of catchment-scale sediment cascades. *Catena*, 70, 49–67.

Fuller, I.C. and Basher, L.R., 2013. Riverbed digital elevation models as a tool for holistic river management: Motueka River, New Zealand. *River Research and Applications*, 29, 619–633.

Fuller, I.C., *et al.*, 2011. Using morphological adjustments to appraise sediment flux. *Journal of Hydrology (New Zealand)*, 50, 59–79.

Fuller, I.C., *et al.*, 2003. Reach-scale sediment transfers: an evaluation of two morphological budgeting approaches. *Earth Surface Processes & Landforms*, 28, 889–903.

Fuller, I.C., *et al*., 2012. Responses to river management? Geomorphic change over decadal and annual timescales in two gravel-bed rivers in New Zealand. *In*: D. Molina ed. *River channels: types, dynamics and changes*. New York: Nova Science, 137–163.

Gibb, J.G., 1978. Rates of coastal erosion and accretion in New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 12, 429–456.

Gillespie, P.A., *et al.*, 2011. Spatial delineation of the depositional footprint of the Motueka River outwelling plume in Tasman Bay, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 45, 455–475.

Gilvear, D.J. and Winterbottom, S.J., 1992. Channel changes and flood events since 1783 on the regulated river Tay, Scotland. *Regulated Rivers, Research and Management*, 7, 247–260.

Goni, M.A., *et al.*, 2008. Terrigenous organic matter in sediments from the Fly River delta-clinoform system (Papua New Guinea). *Journal of Geophysical Research, Earth Surface*, 113, F01S10. doi:10.1029/2006JF000653.

Handley, S., 2006. *An analysis of the historical impacts and composition of the benthic environment of Tasman and Golden Bays*. NIWA Client Report NEL2006–002 for Tasman District Council. Christchurch: National Institute of Water and Atmospheric Research.

Hayes, J.W., 1995. Spatial and temporal variation in the relative density and size of juvenile brown trout in the Kakanui River, North Otago, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 29, 393–407.

Hicks, D.M., 1990. Suspended sediment yield from pasture and exotic forest basins. *In*: *Abstracts New Zealand hydrological society symposium*, 20–23 November, Taupo.

Hicks, D.M. and Basher, L.R., 2008. The signature of an extreme erosion event on suspended sediment loads: Motueka River Catchment, South Island, New Zealand. *In*: J. Schmidt, T. Cochrane, C. Phillips, S. Davies, and L. Basher, eds. *Sediment dynamics in changing environments*. Christchurch: IAHS Publication 325, 184–191.

Hicks, M., Shankar, U., and McKerchar, A., 2003. Sediment yield estimates: A GIS tool. *Water & Atmosphere*, 11, 26–27.

Hicks, D.M., *et al.*, 2011. Suspended sediment yields from New Zealand rivers. *Journal of Hydrology (NZ)*, 50, 81–142.

Jellyman, D.J., Unwin, M.J., and James, G.D., 2003. *Anglers' perceptions of the status of New Zealand lowland rivers and their trout fisheries*. NIWA Technical Report 122. Wellington: National Institute of Water and Atmospheric Research.

Jenkins, C., 2010. *Does the El Nino Southern Oscillation (ENSO) influence the magnitude and frequency of flooding in Southland, New Zealand?* Unpublished Honours dissertation. Massey University.

Jowett, I.G., 1995. Spatial and temporal variability of brown trout abundance: a test of regression models. *Rivers*, 5, 1–12.

Kondolf, G.M., Piégay, H., and Landon, N., 2002. Channel response to increased and decreased bedload supply from land use change: contrasts between two catchments. *Geomorphology*, 45, 35–51.

Lane, S.N., *et al.*, 2007. Interactions between sediment delivery, channel change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms*, 32, 429–446.

Leopold, L.B., 1992. Sediment size that determines channel morphology. *In*: P. Billi, *et al.*, eds. *Dynamics of gravel-bed rivers*. Chichester: Wiley, 297–311.

Liébault, F., *et al.,* 2005. Land-use change, sediment production and channel response in upland regions. *River Research and Applications*, 21, 739–756.

Liébault, F., *et al.*, 2008. Tributaries and the management of main-stem geomorphology. *In*: S.P. Rice, A.G. Roy, and B.L. Rhoads, eds. *River confluences, tributaries and the fluvial network*. Chichester: John Wiley & Sons, 243–270.

Marston, R.A., *et al.*, 1995. Channel metamorphosis, floodplain disturbance and vegetation development, Ain River, France. *Geomorphology*, 13, 121–132.

McDonald, A.M., *et al.*, 2004. Rivers of dreams, on the gulf between theoretical and practical aspects of an upland river restoration. *Transactions of the Institute of British Geographers*, NS29, 257–281.

Mitchell, J.S., 1987. *Tasman sediments*. New Zealand Oceanographic Institute Chart, Coastal Series 1:200,000.

Mueller, M., 1990. *Golden Bay coastal erosion*. Report for Nelson Marlborough Regional Council, Tasman District Council and Department of Conservation, Nelson.

Newson, M.D. and Large, A.R.G., 2006. 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms*, 31, 1606–1624.

Petit, F., Poinsart, D., and Bravard, J.P., 1996. Channel incision, gravel mining and bedload transport in the Rhone River upstream of Lyon, France. *Catena*, 26, 209–226.

Phillips, C., Marden, M., and Basher, L., 2012. Plantation forest harvesting and landscape response – what we know and what we need to know. *New Zealand Journal of Forestry*, 56, 4–12.

Piégay, H., *et al.*, 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. *River Research and Applications*, 21, 773–789.

Piégay, H., *et al.*, 2004. Contemporary changes in sediment yield in an alpine mountain basin due to afforestation (the upper Drôme in France). *Catena*, 55, 183–212.

Pont, D., *et al.*, 2009. Conceptual framework and interdisciplinary approach for the sustainable management of gravel-bed rivers: the case of the Drôme river basin (S.E. France). *Aquatic Sciences*, 71, 356–370.

Raven, E.K., Lane, S.N., and Bracken, L.J., 2010a. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. *Progress in Physical Geography*, 34, 23–25.

Raven, E.K., Lane, S.N., and Ferguson, R., 2010b. Using sediment impact sensors to improve the morphological sediment budget approach for estimating bedload transport rates. *Geomorphology*, 119, 125–134.

Richardson, J., *et al.*, 2013. Holocene river response to regional climate forcing in the Southern hemisphere: evidence from New Zealand. *Quaternary Science Reviews*, 69, 8–27.

Rinaldi, M., Piégay, H., and Surian, N., 2011. Geomorphological approaches for river management and restoration in Italian and French Rivers. *In*: A. Simon, S.J. Bennett, and J.M. Castro, eds. *Stream restoration in dynamic fluvial systems: scientific approaches, analyses and tools*. Geophysical Monograph Series, 194. Washington, DC: American Geophysical Union (AGU), 95–113.

Sriboonlue, S. and Basher, L., 2003. *Trends in bed level and gravel storage in the Motueka River 1957–2001: a progress report on results from analysis or river cross section data from the upper and lower Motueka River.* Nelson: Manaaki Whenua Landcare Research.

Surian, N., 1999. Channel change due to river regulation, the case of the Piave River. *Earth Surface Processes and Landforms*, 24, 1135–1151.

Surian, N. and Rinaldi, M., 2003. Morphological response to river engineering and management in alluvial channels in Italy. *Geomorphology*, 50, 307–326.

Vale, S.S. and Fuller, I.C., 2009. Morphological budgeting in the Motueka River: analysis of technique. *GeoScience*, 2009/1, 1–17. Available from: http://muir.massey.ac.nz/handle/10179/1119

Winterbottom, S.J., 2000. Medium and short-term channel change on the Rivers Tay and Tummel. *Geomorphology*, 33, 195–208.

Wishart, D., Warburton, J., and Bracken, L., 2008. Gravel extraction and planform change in a wandering gravel-bed river: the river wear, northern England. *Geomorphology*, 94, 131–152.

Wyzga, B., 1993. River response to channel regulation, case study of the Raba River, Carpathians, Poland. *Earth Surface Processes and Landforms*, 18, 541–556.

Young, R., 2003. Is everything rosy on the Mot? *Fish & Game New Zealand*, 39, 60–63.

Ziliani, L. and Surian, N., 2012. Evolutionary trajectory of channel morphology and controlling factors in a large gravel-bed river. *Geomorphology*, 173–174, 104–117.