Estimating the spatial distribution of sediment concentration in the Manawatu River, New Zealand, under different land-use scenarios

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Abstract To mitigate sedimentation in waterways, catchment-wide approaches to reducing soil erosion are required. We propose a method to estimate sediment concentration at mean and high discharge, at the subcatchment level, resulting from scenarios of land uses. Sediment concentration is predicted as a function of discharge and sediment yield. The discharge was estimated for 655 subcatchments of the Manawatu River by fitting a regression model between mean annual discharge and mean annual rainfall for 21 gauging sites. The sediment yield was derived from a long-term mean erosion rate model that took into consideration rainfall, land cover, and erosion terrains. The correlation coefficients between the predicted sediment concentration from our model, and the sediment concentration estimated from the rating curves at mean and high discharge, were 0.84 and 0.77, respectively. The model prediction was used to assess the implications of land use change and farm plans scenarios on sediment concentrations in the Manawatu River.

Key words sediment concentration; spatial distribution; land use; land management; water quality; soil erosion

INTRODUCTION

Over the past 150 years, since European settlement, much of the original indigenous forest in New Zealand has been converted to pastoral agriculture. In hill country, where tree roots are important for stabilising slopes, deforestation has led to increased soil erosion and consequently increased sedimentation in waterways. High sedimentation smothers gravel substrates, and thus reduces the amount of habitat available to fish and invertebrates (Suren & Jowett, 2001). High sediment concentration in water reduces the penetration of photosynthetically active light (Crowe & Hay, 2004), and can affect fish feeding and behaviour (Rowe & Dean, 1998). It also has a negative impact on the recreational value of the rivers. In major catchments where stop banks have been constructed, deposition of sediment in floodways reduces flood capacity, thereby increasing flood risk. Increased storminess associated with climate change will generally increase erosion rates and can only exacerbate the negative environmental effects associated with increased sedimentation of waterways.

To mitigate sedimentation in waterways, catchment-wide approaches to reducing soil erosion are required. Numerous catchment-scale models of erosion and sedimentation have been developed to assist planning of the mitigation process (Merritt *et al.*, 2003). However, at small time steps and across whole catchments, the processes to be modelled become very complex and there are usually insufficient data for adequate parameterisation (Wilkinson *et al.*, 2006). To overcome this problem, Wilkinson *et al.* (2004) developed a catchment-scale model (SedNet) of long-term averages of erosion, sediment yield and sediment storage, all calculated at the subcatchment level. SedNet requires estimates of erosion for the main processes (bank erosion, hillslope erosion, gully erosion, and flood plain deposition) as well as information relating to catchment hydrological processes (mean discharge and extent of flood plain). The model permits the evaluation of different land-use and land-management scenarios on sediment yield (Bartley *et al.*, 2004; Wilkinson *et al.*, 2005).

While SedNet can estimate sediment yield, it does not predict sediment concentration at indicative discharges, which is an important water quality indicator for aquatic ecosystems (Davies-Colley & Wilcock, 2004). In this paper, we extend the SedNet model to permit the estimation of sediment concentrations for two indicative discharges: mean discharge and the discharge exceeded 5% of the time. This is achieved by regionalising sediment rating curves with mean discharge and mean sediment yield; the mean discharge in turn is regionalised with mean annual rainfall. We demonstrate our approach by evaluating the effect of land-use change and farm plan scenarios on the spatial distribution of sediment concentration in the Manawatu River of New Zealand.

METHODS

Study area

The Manawatu catchment covers 5885 km^2 and is located in the southern part of the North Island of New Zealand. Mean annual rainfall ranges from 1000 mm on the plains to 3000 mm in the Tararua ranges. The catchment is monitored with 21 gauging sites recording discharge, 10 of which are surveyed for suspended sediment concentrations during flood events (Fig. 1). The basic units of calculation are stream links in the river network and associated subcatchments. The river network and subcatchments were defined from a 15-m grid digital elevation model (DEM), generated from 20-m contours, and hydrologically consistent with a 1:50 000 map-based river network. Flow direction and flow accumulation were produced in ArcHydro of ArcGIS (Maidment, 2002). The river network was produced by applying a drainage area threshold of 20 km^2 to flow accumulation, resulting in 211 stream links.

Sediment source

SedNet evaluates sediment inputs from hillslope erosion, gully erosion and bank erosion for each stream link. In this paper, we simplify the sediment budget by assuming that in the long term there

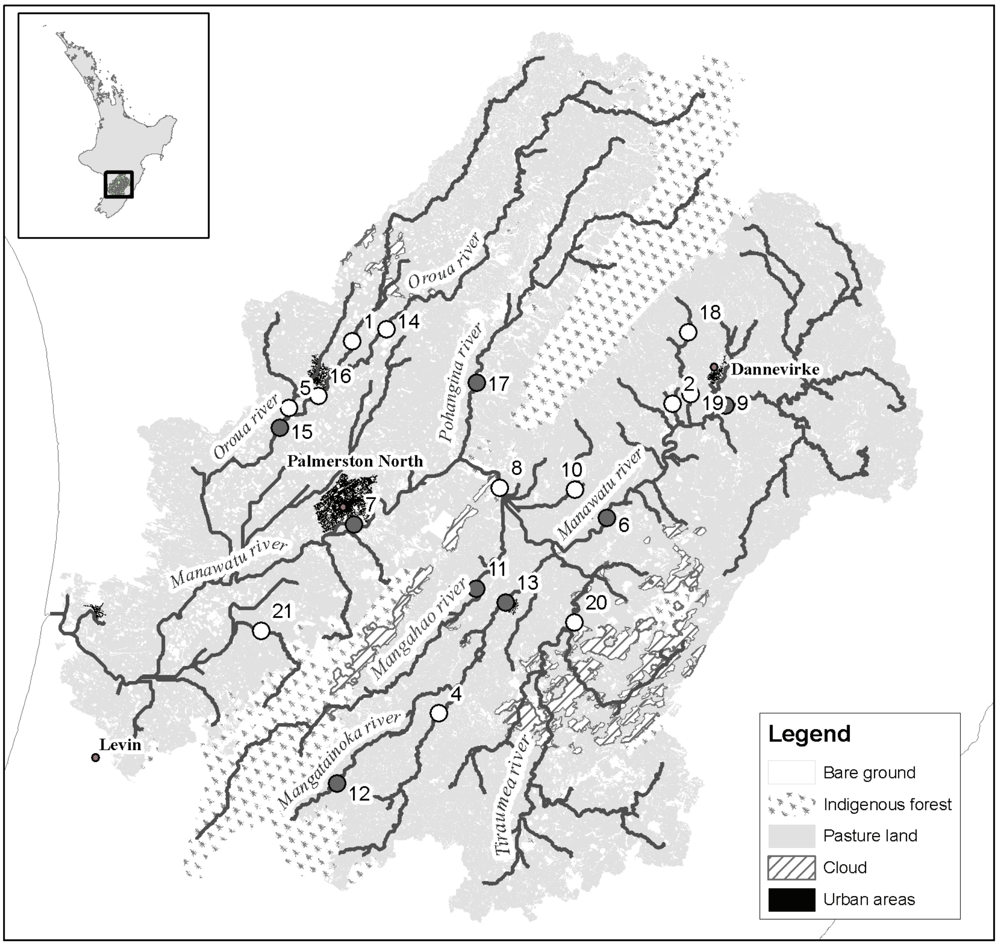

Fig. 1 Location of the gauged sites in the Manawatu catchment. The white dots shows sites with daily flow recorders, the black dots show sites surveyed for suspended sediment concentrations.

is no net change of storage on the flood plain; that is, bank erosion and flood-plain deposition are approximately balanced within the 20 km^2 drainage areas. Rosser (2008) found bank erosion in the Waikohu River to be an order of magnitude less than the total sediment yield; and even in the Pohangina subcatchment, where we observed in historical aerial photographs large increases in flood-plain volume over 50 years, the measured difference between flood-plain deposition and bank erosion was only 25% of the total sediment yield. The remaining sediment sources are hillslope and gully erosion. The sum of these two was estimated using a model of long-term mean erosion rate (Dymond & Betts, 2008), denoted by $e(x, y)$, where x and y are geographic coordinates.

$$e(x, y) = \kappa(x, y)\, C(x, y) R^2 (x, y) \qquad (1)$$

where $\kappa(x,y)$ is a constant depending on erosion terrains, $R(x,y)$ is the mean annual rainfall; and $C(x,y)$ is a cover factor relative to forest.

Erosion terrains were produced by partitioning New Zealand on the basis of rock type, landform and rainfall, at the scale of 1:50 000, to produce areas with similar erosion processes, by amalgamating land-use capability units from the New Zealand Land Resource Inventory (Eyles, 1983). A three-level hierarchical classification was used. For the North Island, we differentiated nine groups at the top level on the basis of landform and slope. At the second level, 26 groups were differentiated on rock type. At the third level we differentiated fifty-two groups on the basis of erosion processes and further detail of rock type. In the Manawatu catchment, there are 28 different erosion terrains. The κ coefficients were derived for each erosion terrain from a national data set of sediment yield data (Dymond & Betts, 2008).

The annual rainfall factor R was derived from a national map of mean annual rainfall on a 100-m grid (Leathwick *et al.*, 2003).

Studies in North Island hill country have shown that when forest is converted to pasture, long-term erosion rates increase by approximately an order of magnitude (Page & Trustrum, 1997), and so does the magnitude of landsliding events (Dymond *et al.*, 2006). The cover factor, $C(x,y)$, was therefore derived as follows:

$$C(x,y) \begin{cases} = 1 \text{ if land cover is woody vegetation} \\ = 10 \text{ if land cover is herbaceous vegetation} \\ = 10 \text{ if land cover is bare ground} \end{cases} \qquad (2)$$

A map of cover factor at 1:50 000 scale (i.e. 15-m pixels) was produced for the Manawatu catchment from ETM+ satellite imagery using the method of Dymond & Shepherd (2004). Imagery dates varied between the summers of 1999/2000 and 2001/2002.

Sediment delivery to the river

Sediment delivery ratio is defined as the ratio of sediment volume delivered to the stream network divided by the volume of soil eroded (Walling, 1983). We applied a simple sediment delivery ratio model as follows:

$$E_s(x, y) = e(x, y)\, s(x, y) \qquad (3)$$

where $E_s(x,y)$ is the specific sediment yield (t km^2 year^{-1}), and
$s(x,y) = 1$ if there is delivery to the stream network, but
$s(x,y) = 0$ if there is deposition in the landscape

Pixels in the DEM were labelled as delivering if flow lines from the pixel reached a stream (30 ha minimum drainage area) without encountering an area of deposition defined by two consecutive pixels with slope under 5 degrees (pixels within a 15-m buffer zone were considered connected to the river system). These parameters were empirically determined by optimising the goodness of fit between the modelled and the actual connectivity in the Waipaua catchment, New Zealand.

Hydrological regionalisation

Estimates of mean discharge are required for each river link. Since discharge measurements are only available at a small number of gauged flow sites in a catchment, regression methods are

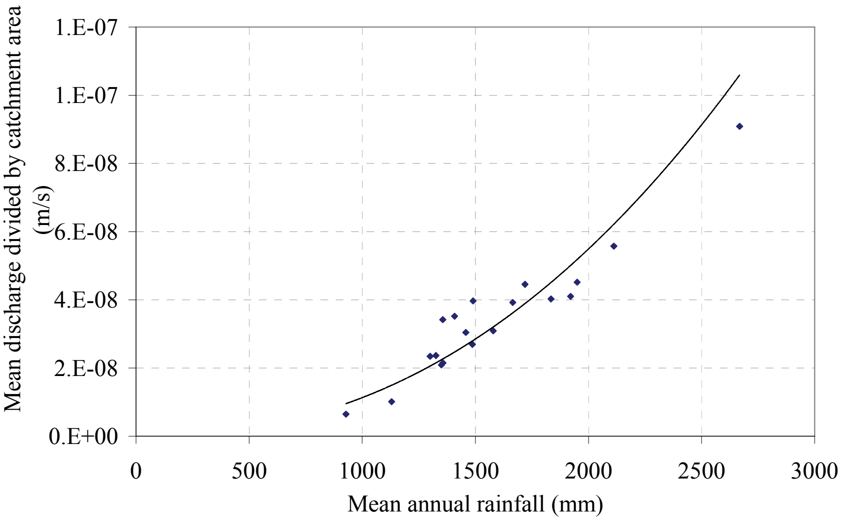

Fig. 1 Plot of mean discharge ($m^3 s^{-1}$) divided by catchment area (m^2) *versus* mean annual rainfall (mm) of catchment for gauged flow sites in the Manawatu catchment.

applied to predict flow at ungauged links in the network (Young *et al.*, 2001). We regressed mean specific discharge at gauged sites on mean annual rainfall (Fig. 2). The regression equation is:

$$\frac{Q_m}{A} = 2\times10^{-15} R^{2.3} \quad (\rho = 0.92) \tag{4}$$

where Q_m is mean discharge, A is catchment area, R is mean annual rainfall and ρ is the correlation coefficient.

The discharge exceeded 5% of the time, Q_{hd}, was related to mean discharge using an empirical regression at the gauged sites as follows:

$$Q_{hd} = 2.8\ Q_m\ (\rho = 0.99) \tag{5}$$

Regionalisation of sediment rating curves

A commonly used equation for sediment rating curves is a power function (Syvitski *et al.*, 2000):

$$S = bQ^a \tag{6}$$

where b and a are two dimensionless parameters called the sediment rating coefficient and exponent. Once a sediment rating curve is established from concurrent measurements of sediment concentration and discharge over a range of discharges, it is possible to estimate sediment concentration from discharge. Sediment rating curves were estimated for seven of the gauged sites in the Manawatu (Fig. 3). The other sites had insufficient suspended sediment data for estimating a rating curve.

Hicks *et al.* (2000) found the sediment rating coefficient at a site on the Waipaoa River, New Zealand, after cyclone Bola changed in direct proportion to the sediment yield, so we rewrote equation (6) as:

$$S = b'\overline{E}_s Q^a \tag{7}$$

where a, b' are parameters to estimate, and $\overline{E}_s$ is the mean specific sediment yield over the upstream catchment of the link considered, calculated from equations (1), (2) and (3).

The exponent a is relatively constant over the seven gauged sites (Fig. 2), so was set to the mean for each stream link (a = 1.56, std. dev. = 0.26). The rating coefficient, b', decreases with increasing mean discharge (when small rivers are in flood they carry significant sediment at discharges much lower than large rivers) (Fig. 4), so we hypothesised a linear relationship in log transform between b' and mean discharge Q_m:

$$\log(b') = \alpha \log(Q_m) + \beta \tag{8}$$

where α and β are two parameters to identify.

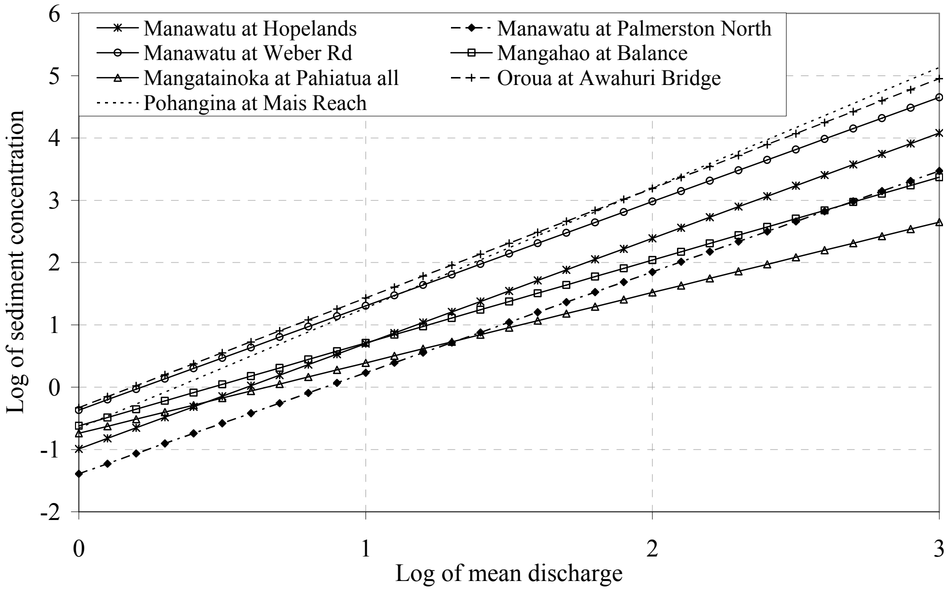

Fig. 2 Sediment rating curves for sites in the Manawatu gauged for sediment concentration.

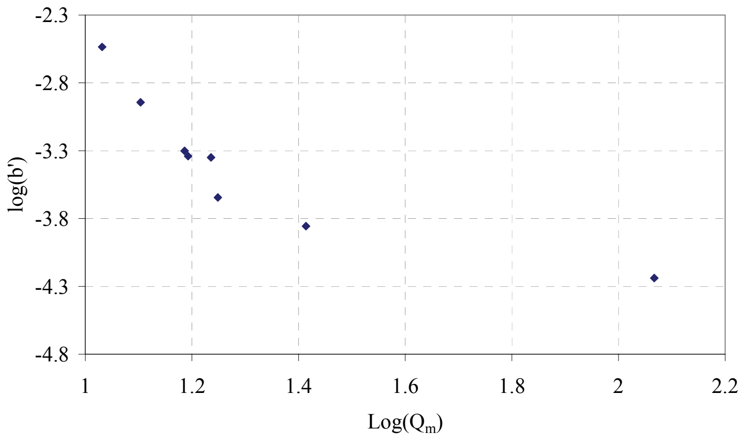

Fig. 3 Relationship between b' and Q_m.

The two parameters α and β were estimated using the solver package in Excel Microsoft Office, by minimising the difference between predicted and observed sediment concentrations at Q_m of the seven gauged sites. The observed sediment concentration was calculated from the sediment rating curves by selecting the sediment concentration corresponding to the mean discharge.

The estimated parameters were:

$$\alpha = -0.81, \beta = 2.44 \qquad (9)$$

RESULTS

Model accuracy assessment

The correlation coefficient between the predicted intercept $b'E$ and the observed intercept b in log transform for the seven gauged sites is 0.86. A comparison of predicted sediment concentration at Q_m and Q_{hd} from our model, and sediment concentration estimated from the rating curves at seven gauging sites, is shown in Fig. 5. The correlation coefficients are 0.84 and 0.77 for SC(Q_m) and SC(Q_{hf}), respectively. Given the large errors typically associated with estimating sediment concentration from rating curves (Horowitz, 2003), the predicted sediment concentrations from our model show acceptable agreement. More measurement sites are required to fully confirm this. The agreement is acceptable along the regression except for sites 15 and 17. Note also that site 7 is an isolated prediction with a higher range of sediment concentration as it is located on the main stem of the Manawatu catchment.

Table 1 Sediment rating curve coefficients for the gauged sites in the Manawatu catchment.

Site number	Site name	$\bar{E}_s$ (t/km^2/yr)	Log(a)	Log(b)	95% confid. interval log(b)	Log($b'E$)
6	Manawatu at Hopelands	735	1.69	–0.99	–1.16 to –0.82	*–0.65*
7	Manawatu at Palmerston North	706	1.62	–1.39	–1.81 to –0.97	–1.27
9	Manawatu at Weber Rd	939	1.67	–0.37	–0.93 to 0.19	–0.34
11	Mangahao at Balance	479	1.33	–0.62	–0.85 to –0.39	–0.63
13	Mangatainoka at Pahiatua all	410	1.13	–0.74	–1.12 to –0.35	–0.75
15	Oroua at Awahuri Bridge	413	1.76	–0.33	–0.44 to –0.22	*–0.62*
17	Pohangina at Mais Reach	639	1.93	–0.66	–1.11 to –0.21	–0.55

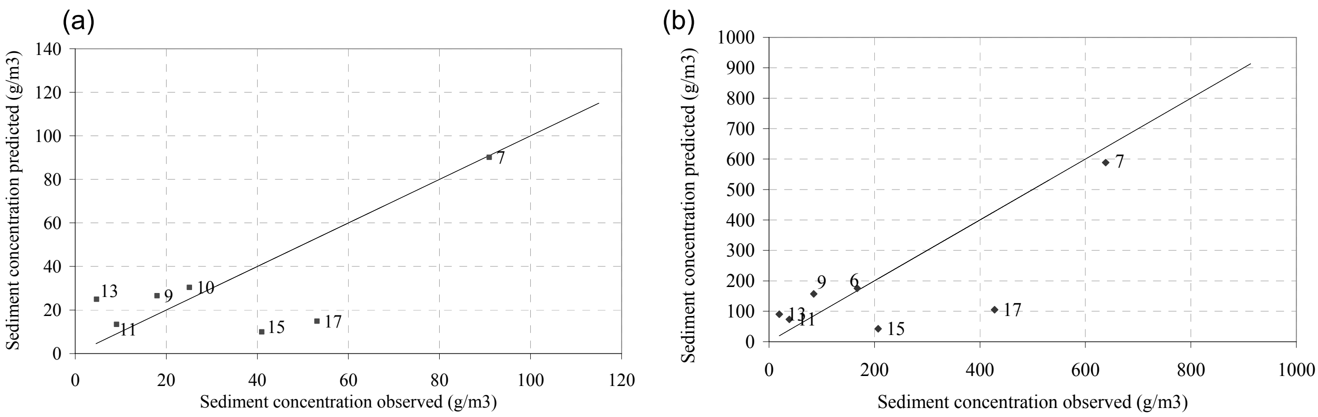

Fig. 4 Predicted *versus* observed sediment concentration at: (a) mean discharge, and (b) discharge exceeded 5% of the time.

Land-use scenarios

We used the model to evaluate the effect of land use on sediment concentration in the Manawatu river. Three land cover scenarios were considered:

(1) a historic scenario, where all the Manawatu catchment is covered in indigenous forest (Leathwick *et al.*, 2003);

(2) a present land-use scenario where most of the hill country has been converted from indigenous forest to pastoral agriculture (this came from classification of Landsat TM imagery dated 1999–2002);

(3) a farm plan scenario. The local Regional Authority is encouraging the implementation of farm plans, designed to reduce erosion and increase productivity. Previous work has identified priority farm plans in the catchment by ranking them in order of areas of highly-erodible land. This scenario assumes the implementation of the first 500 farm plans with each farm plan reducing sediment load by 70%. Hawley & Dymond (1988) reported 80% for landsliding; Hicks (1995) reported 50–80% for landsliding and 30–80% for gullying. The 500 farm plans are mostly located on the eastern and northern part of the catchment.

Figure 6 shows the spatial pattern of sediment concentration at mean discharge for the three different land-use scenarios. Under the historic scenario, sediment concentration in the river is less than 18 g/m^3 (at Palmerston North), with higher concentrations on the main stem of the Manawatu River and on the Mangahao River. The present land-use scenario shows a range of sediment

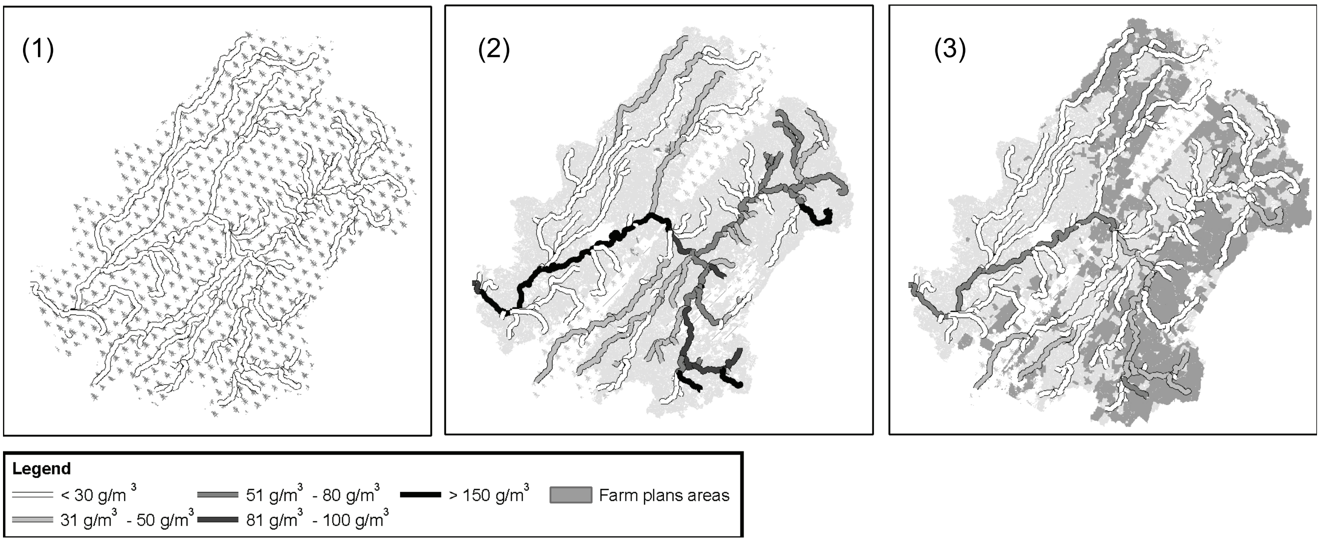

Fig. 5 Comparison of sediment concentration (g/m^3) at mean discharge using three scenarios: (1) historic scenario, (2) present land-use scenario, (3) farm-plan scenario (500 farm plans shown in dark grey).

concentrations up to a maximum of 120 g/m^3 at Palmerston North. The Upper Manawatu and Tiraumea tributaries also have high sediment concentration. The farm plan scenario shows a reduction of sediment concentration at Palmerston North, to 58 g/m^3. At the outlet of the Manawatu River, the sediment concentration is also reduced from 100 g/m^3 to 50 g/m^3.

DISCUSSION

Although the model has been successfully used to evaluate the effect of land-use change and farm plan scenarios on sediment concentration, there is considerable uncertainty associated with the predictions as shown in Fig. 5. The model is based on regionalisation of sediment rating curves, which are well known to involve large uncertainty primarily due to hysteresis effects (Asselman, 2000; Horowitz, 2003); and the regionalisation derives from only eight gauged sites throughout the catchment. There is also uncertainty associated with the regionalisation of mean annual flow on mean annual rainfall and catchment area. Gauged catchments may not represent the full range of rainfall and catchment area (Wilkinson *et al.*, 2006), and there might be unrealistic estimates for rivers with low flows.

However, it is possible that predictions are more accurate than shown in Fig. 5 because of uncertainty in the measurements themselves: measurements rely on sediment concentration rating curves that have inherent large uncertainty. Independent data of continuously measured turbidity, recorded by Horizons Regional Council (Bartsch, 2008), confirm the general spatial trends of predicted sediment concentrations: that is, turbidity generally increases with increasing catchment area – it is highest in the main channel of the Manawatu River; closely followed by the Tiraumea River.

The model can be used, rapidly and simply, to predict changes in sediment concentration anywhere in the Manawatu catchment in response to land-use change or the implementation of farm plans. This high flexibility enables the model to be reconfigured quickly to explore new land-use scenarios proposed by management groups. The graphical output of the model has great potential as an aid in understanding and communication of the complex spatial relationship between land use and water quality. In particular, it provides a tool for prioritising land-use change and implementation of farm plans to achieve the greatest water quality gains. In future, we plan to further extend the model to turbidity, in addition to sediment concentration, as there are well established linear relationships between them (Bartsch, 2008).

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