Will human catalysts or climate change have a greater impact on the sediment load of the Waipaoa River in the 21st century?

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Abstract We use a climate-driven hydrologic-transport model, HydroTrend, that is able to compute water and sediment discharges in daily increments, to assess the effect that the change in climate (mean annual temperature and precipitation) forecast for the 2030s and 2080s will have on the water discharge and suspended sediment load of the Waipaoa River, New Zealand. Given the prospects of a warmer and drier climate, the magnitude of extreme events, such as the one-in-200 year flood, could be reduced by as much as 63–68%, and the mean flow in the Waipaoa River could decline to 78–96% of its present value by the 2030s and to 64–100% by the 2080s. Our simulations indicate that the mean annual suspended sediment load could be 91–108% and 84–126% of the present value (13.4 ± 7.3 Mt year^{-1}) by the 2030s and 2080s, respectively. Given the large variation in the present mean annual suspended sediment load, the former change may be difficult to discern and, overall, the forecast effect of 21st century climate change on the suspended sediment load of the Waipaoa River is less than the magnitude of the change that is thought to have occurred at the beginning of the Anthropocene. Thus the legacy of past human activities will continue to dominate.

Key words modelling; HydroTrend; sediment transport; climate change; suspended sediment; peak discharge

INTRODUCTION

It has been demonstrated that humans have had a significant impact on patterns of erosion and sedimentation, and current rates of human-induced erosion in agricultural landscapes may be as much as one to two orders of magnitude larger than natural rates (Wilkinson & McElroy, 2006; Montgomery, 2007). However, it has proved difficult to use time-varying records to quantify the impact human activity has had on drainage basin sediment yield, and there is increasing concern that over the next century climate change will increase the rate at which sediment is delivered to stream channels (Walling & Fang, 2003; Nearing *et al*., 2005). An alternative way of examining these issues is to use a numerical model to simulate the impact different categories of environmental change have on fluvial sediment discharge (Syvitski *et al.*, 2005a; Syvistki & Milliman, 2007).

Our focus in this paper is on the 1987-km^2 Waipaoa River basin, New Zealand (Fig. 1), upstream from the gauging station at Matawhero, a locale in which the sedimentary record documents the landscape response to natural and anthropogenic change in the period before and after the initial Polynesian settlement of New Zealand, approx. AD 1250–1300 (Gomez *et al.*, 2007). The basin is underlain by thrust-imbricated Late Cretaceous and Early Tertiary mudstone and argillite, Early Cretaceous greywacke, and a cover sequence of poorly consolidated Neogene marine sedimentary rocks (Mazengarb & Speden, 2000). It is subject to a maritime climate that is periodically perturbed by cyclonic storms of tropical origin and today only ~2.5% of the basin remains under native forest because, beginning in the late 1820s, European colonists converted most of the land to pasture. For these reasons, the Waipaoa River ranks among the Earth's highest-yield fluvial systems, with a mean annual suspended sediment discharge of 15.0 ± 6.7 Mt (Hicks *et al.*, 2000). Summary information about the Waipaoa River basin is provided in Table 1.

Efforts to research the cause and alleviate the impact of accelerated erosion in the Waipaoa River basin have a long history (Gage & Black, 1979), and many local planning and policy decisions are necessarily founded on the avoidance or mitigation of adverse effects on the environment (Ministry for the Environment, 2004) including the legacy of deforestation and climate change driven by global warming. Previously we used a climate-driven transport model to

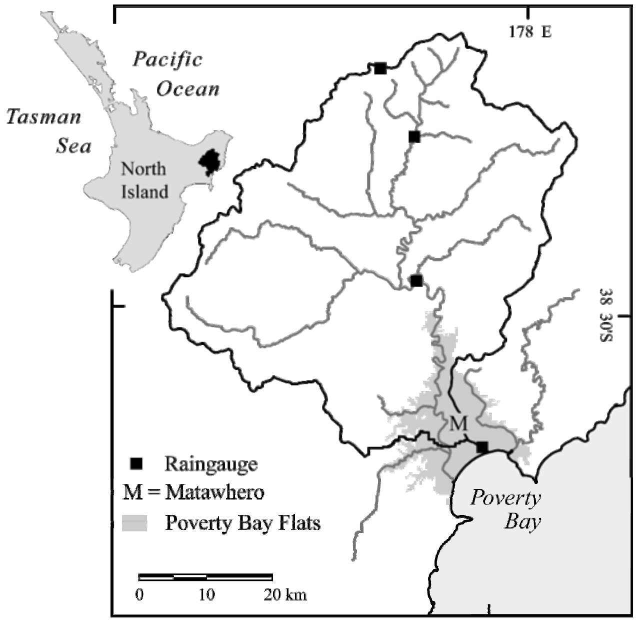

Fig. 1 Location of sites in the Waipaoa River basin from which the hydrometeorological data used to define boundary conditions for the model runs were obtained (after Kettner *et al.*, 2007).

Table 1 Summary information on the Waipaoa River basin and climate projections used in the simulations.

Waipaoa	Present	Model scenarios: 2030s	2080s
Area (km^2)	1987		
Relief (m)	1190		
Mean water discharge, $\overline{Q}_T$ ($m^3 s^{-1}$)	48.4		
Peak flow ($m^3 s^{-1}$)	4200		
Mean annual suspended sediment, $\overline{Qs}$ ($kg s^{-1}$)[a]	13.4 ± 7.3		
Mean annual precipitation (m)[b]	1.59	1.32; 1.39; 1.45; 1.52; 1.59	1.1; 1.24; 1.38; 1.51; 1.65
Mean annual temperature (°C)[b, c]	11.8	12.0; 12.5; 13.0	12.3; 13.6; 14.9

[a] Estimated using HydroTrend; [b] basin-wide average; [c] assuming the projected change in mean annual temperature from 1990 to the 2030s is 0.2–1.4°C, and for the 2080s it is 0.6–3.8°C.

disentangle the impact of anthropogenic activity from other perturbations to the catchment environment that influenced basin sediment yield in the past 3000 years (Kettner *et al.*, 2007). Herein we use these results, in combination with information derived from new simulations, to quantify the relative impact that human activities have had on the suspended sediment load of the Waipaoa River in the past, and global warming is projected to have in the future. The model, HydroTrend, generates water discharge and sediment load time series, as a function of climatic and local catchment characteristics that influence the hydrology of the contributing river (Kettner & Syvitski, 2008), and we base our forecast on the regional climate projections made for the 2030s and 2080s by the New Zealand Ministry for the Environment (2004; Table 1).

THE NUMERICAL MODEL

Governing equations

HydroTrend is a climate-driven water balance and transport model that simulates daily time series of water discharge and sediment load at the river outlet. Information required to implement the model comprises the physical properties (hypsometry, relief) of the drainage basin in question, together with the following biophysical parameters: monthly and annual temperature and basin-wide precipitation and their variation; and the extent and type of vegetation cover. The climatological statistics were generated using data from four stations, weighted by elevation (Fig. 1).

In the context of this paper, only two key equations are discussed below and we refer the reader to Kettner & Syvitski (2008) and Kettner *et al.* (2007) for a complete description of the model and details on how it has been applied to the Waipaoa basin. Daily water discharge, $Q_{[i]}$ (m^3 s^{-1}) where i is the time step, can be calculated with reference to five hydrological processes, three of which, the discharge generated by rain, Q_r, the groundwater, Q_{gr}, and the discharge lost by evapotranspiration, Q_{evap}, play a role in the Waipaoa River basin:

$$Q_{[i]} = Q_{r[i]} \pm Q_{gr[i]}, - Q_{evap[i]} \quad (1)$$

The long-term average suspended sediment load at the river mouth, $\overline{Qs}$ (kg s^{-1}), is calculated using a modified version of the empirical relation by Syvitski *et al.* (2003):

$$\overline{Q_s} = (veg)\alpha_6 \hat{Q}_T^{\alpha_7} \hat{R}^{\alpha_8} e^{k_2 \hat{T}} \quad (2)$$

where *veg* is a dimensionless vegetation-erosion index, that is equivalent to the term Syvitski & Milliman (2007) used to characterize catchment geology, and accounts for the effect that a change in the vegetation cover has on erosion rates and sediment production from highly erodible lithologies; the nondimensional water discharge, $\hat{Q} = \left(\frac{\overline{Q_T}}{Q_0}\right)$ $Q_0 \equiv 1$ m^3 s^{-1}; the nondimensional basin relief, $\hat{R} = \left(\frac{R}{R_0}\right)$ with $R_0 \equiv 1$ m; the nondimensional average basin temperature, $\hat{T} = \left(\frac{\overline{T}}{T_0}\right)$ with $T_0 \equiv 1°C$. The parameters for this climate zone are, $\alpha_6 = 0.0011$ kg s^{-1} $°C^{-1}$, $\alpha_7 = 0.53$, $\alpha_8 = 1.1$ and $k_2 = 0.06$.

Model validation

Previous work has shown that HydroTrend's simulations have comparable accuracy to the field observations made on multiple rivers, including the Eel River, USA, and Lanyang River, Taiwan (Syvitski & Morehead, 1999; Syvitski *et al.*, 2005b), which are located on tectonically active margins, and rivers draining the Apennines (Syvitski & Kettner, 2007). To evaluate the performance of HydroTrend under present conditions in the Waipaoa River basin, Kettner *et al.* (2007) used a graphical comparison between ranked daily values of simulated water discharge and ranked observations for an equivalent 25-year period of record and a binned Chi-square analysis to show the simulated data replicate the frequency and distribution of water discharges (Fig. 2(a)), and portray the same order of goodness-of-fit to the field data as a comparison between different sections of the observed water discharge record. The variation in the daily suspended sediment load is portrayed equally well (Fig. 2(b)), and a two-sample Chi-square test indicated that the mean representative χ^2 value of the data–model comparison was less than the critical χ^2 value (Kettner *et al.*, 2007). Variations in suspended sediment concentration with water discharge are also preserved in the model output, which consequently provides a consistent and unexaggerated match to the observed concentrations over the entire range of flows.

Evaluating future climate change

The quantitative estimates of future climate change at large (continental) scales provided by Atmosphere–Ocean General Circulation Models have been statistically downscaled for New Zealand (Ministry for the Environment, 2004), and regional climate projections made for 30-year

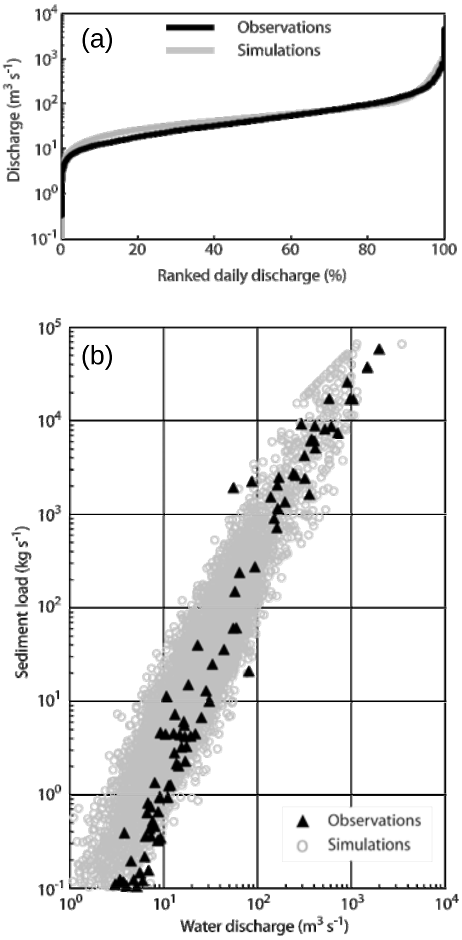

Fig. 2 Comparison of (a) 25 years of ranked daily simulated and observed water discharges, and (b) 39 years of daily simulated and observed suspended sediment concentrations, in the Waipaoa River at Matawhero (after Kettner *et al.*, 2007).

periods centred on 2035 and 2085 (herein referred to as the 2030s and 2080s, respectively). The expectation is that the east coast of New Zealand's North Island will, on average, experience warmer, drier conditions, and the climate projections are expressed in terms of the anticipated range of increase in mean annual temperature and decrease in precipitation (Table 1). Note that we did not incorporate the forecast increase in rainfall intensity, which has less accuracy than the projected decrease in annual rainfall (Ministry for the Environment, 2004). This is because changes in the frequency with which extreme events occur, such as large storms, cannot be obtained directly from the climate model output, and there is correspondingly more uncertainty about the impact climate change may have on extreme events than there is about its impact on average conditions. Any potential sea-level rise induced by global warming over the course of the next century will not substantially influence the total drainage basin area, nor will denudation appreciably alter the basin relief, and these and other physical parameters are assumed to be characterized by present conditions. On this basis we conducted ensemble model runs that incorporate the forecast temperature and precipitation changes for the 2030s and 2080s in an attempt to quantify the impact they may have on basin suspended sediment yield.

RESULTS

In light of the prospects of a warmer, drier climate for the east coast region as a whole, our simulations suggest that the mean flow in the Waipaoa River at Matawhero could decline to between 78 and 96% (average = 87%) of its present value of ~48 $m^3 s^{-1}$ by the 2030s, and to between 64 and 100% (average = 82%) by the 2080s. Figure 3 presents log-Pearson type III peak discharge frequency curves for the 2030s and 2080s for five different values of projected precipitation and mean water discharge, given the forecast decline of precipitation, without taking into account a projected increase in rainfall intensity. As noted above, there is more uncertainty about the impact climate change may have on extreme events than there is about its impact on average conditions, but our simulations suggest that, for example, the one-in-200 year flood could be between 68 and 100% and 63 and 102% of the present (simulated) discharge of 4570 $m^3 s^{-1}$ in the 2030s and 2080s, respectively (the maximum recorded discharge of 4000 $m^3 s^{-1}$ has a recurrence interval of ~70 years on the annual maximum series).

The model output summarizing the projected change in the average annual suspended sediment load of the Waipaoa River during the 2030s and 2080s is presented in Fig. 4(a), for the anticipated range of variation in annual precipitation (*x* axis) and mean annual temperature (*y* axis). As expected, because water discharge, which motivates suspended sediment discharge, is dependent on precipitation, suspended sediment discharge declines as precipitation declines (cf. equation (2)). However, we note that in accordance with the influence temperature has on weathering processes, and rates of soil formation and soil erosion (Syvitski *et al.*, 2003), suspended sediment discharge increases as temperature increases. Accordingly, depending on the relative magnitude of the increase in mean annual temperature and decline in annual precipitation, the mean annual suspended sediment load of the Waipaoa River at Matawhero is projected to be between 92 and 109% of the present value by the 2030s, and between 85 and 128% by the 2080s. Such changes will necessarily occur gradually, but our simulations provide insight into the consequences of the adjustments to particular climate scenarios rather than the time frame required to affect them.

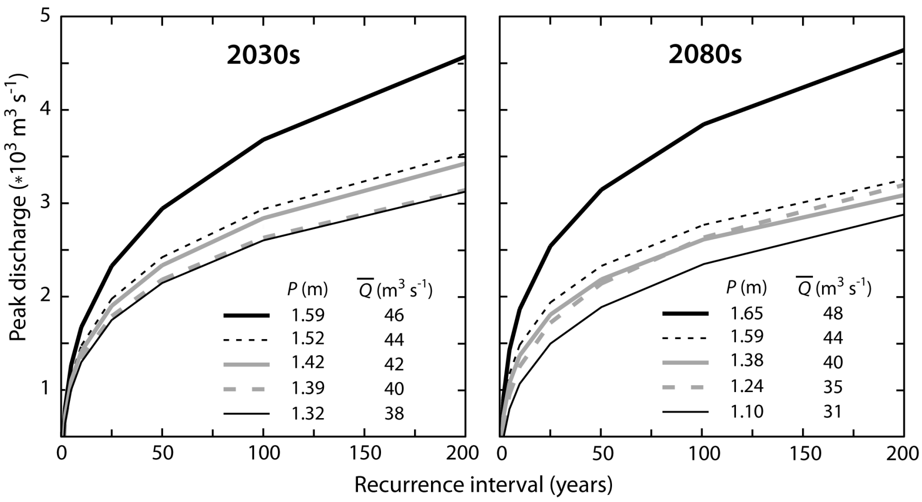

Fig. 3 Simulated log-Pearson type III peak discharge frequency curves and associated average discharge ($\overline{Q}$) for the Waipaoa River at Matawhero for the 2030s and the 2080s assuming the forecast change in precipitation (*P*).

DISCUSSION

We have used a climate-driven hydrologic-transport model to examine the impact that forecast changes in climate may have on the discharge and annual suspended sediment load of the Waipaoa River at Matawhero during the 2030s and 2080s. The issue is of especial local concern because the operational lifetime of the flood control scheme that protects high value agricultural land and property on the Poverty Bay Flats is contingent upon both the magnitude of future floods and the amount of vertical accretion that occurs on berms during flood flows. More generally, there is a need to develop models that can be used to forecast the potential impacts of climate change

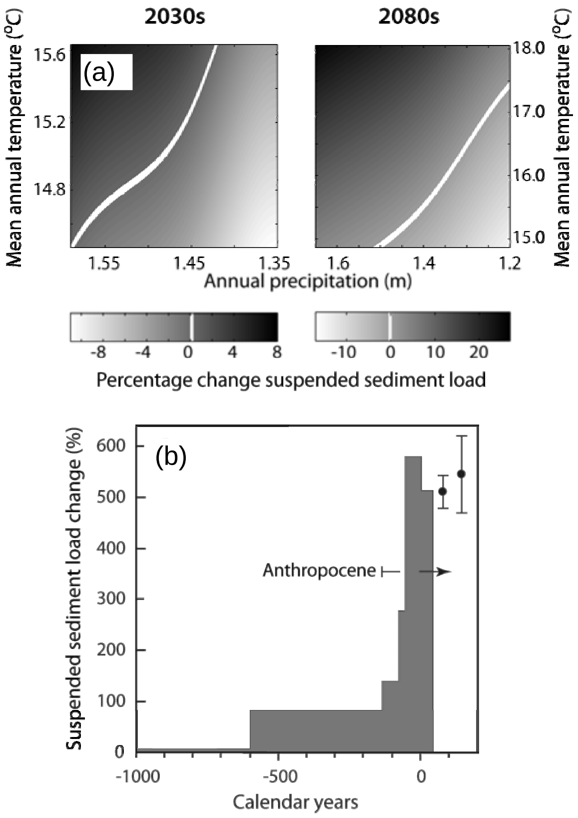

Fig. 4 (a) Potential percentage change in suspended sediment discharge for the 2030s and 2080s compared to the present suspended sediment load of the Waipaoa River, for the forecast changes in temperature and precipitation given in Table 1 (white denotes there is no change in the suspended sediment load; black to dark grey: an increase; and dark to light grey: a decrease). (b) Percentage change in the suspended sediment load of the Waipaoa River (with reference to the period when the landscape was subject only to perturbations by natural events) immediately before and throughout the Anthropocene. The dramatic increase in the period after –135 calendar years (AD 1820) is associated with the arrival of European colonists and the eventual conversion of the basin headwaters to pasture. Zero calendar years equate with AD 1955, the solid dots indicate the mean and the error bars plus/minus one standard deviation of the potential values for the 2030s and 2080s.

on fluvial sediment discharge and help identify its consequences for management decisions on a river-by-river basis. In the latter context, it is also helpful to express the magnitude of future change in the context of changes that have occurred in the past.

In the past, when the landscape of the Waipaoa River basin was relatively stable and subject only to occasional perturbations by natural events such as fires set by lightning strikes and storms, we estimate that the suspended sediment load of the Waipaoa River was between 2.2 ± 4.2 and 2.4 ± 6.1 Mt year^{-1} (cf. Kettner *et al.*, 2007). Thus, by comparison with other small steepland rivers (Milliman & Syvitski, 1992), even prior to the arrival of humans, the Waipaoa River transported a very large amount of suspended sediment for its size. Following the arrival of Polynesian settlers and European colonists, this increased to 4.0 ± 12.7 and 5.3 ± 5.0 Mt year^{-1}, respectively, and, once the basin was deforested, to 15.7 ± 8.8 Mt year^{-1}. The present value is estimated to be 13.4 ± 7.3 Mt year^{-1} and given the large variation in estimates of the contemporary mean annual suspended sediment load (Table 1), the forecast change may be difficult to discern in the 2030s. Viewed against the background of the Late Holocene, in the future the suspended sediment load will still be >500% larger than the load the Waipaoa River transported in the period before the basin was impacted by human activity, and the forecast effect of 21st century climate change is less than the magnitude of the initial change (increase) that occurred at the beginning of the Anthropocene (Fig. 4(b)). Thus the legacy of deforestation will continue to be the dominant influence on the suspended sediment load of the Waipaoa River in the 21st century.

SUMMARY

Simulations conducted using the climate-driven hydrologic-transport model HydroTrend indicate that the forecast increase in mean annual temperature and decrease in annual precipitation during the 21st century could cause the mean flow in the Waipaoa River at Matawhero to decline to 78–96% of its present value by the 2030s, and to 64–100% by the 2080s. The warmer and drier climate might also reduce the one-in-200 year peak flood to ~84% of its present (simulated) peak flood discharge. The mean annual suspended sediment load of the Waipaoa River at Matawhero could be 92–109% and 85–128% of the present value by the 2030s and 2080s, respectively. The forecast change may be difficult to discern in the 2030s and it remains that the forecast effect of 21st century climate change on the suspended sediment load of the Waipaoa River is less than the magnitude of the initial change that is thought to have occurred at the beginning of the Anthropocene, and the legacy of deforestation will therefore continue to dominate.

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