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Land-use impacts on catchment erosion for the Waitetuna catchment, New Zealand

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Abstract In this study the detailed physically-based model SHETRAN was applied and tested for the Waitetuna catchment of the Raglan Harbour/Whaingaroa (170 km^2), with the aim of representing signals in terrestrial sediment generation. Records of streamflow, turbidity, and transported sediment monitored under intensive rainfall conditions served as validation data. We used model set-ups using different land-use scenarios to explore land-use impacts on sediment generation and to suggest catchment management alternatives to minimize impacts of erosion and sediment transport on the Raglan estuary.

Key words land-use change; catchment erosion; SHETRAN; Raglan, New Zealand

INTRODUCTION

New Zealand, located at the interface between the Pacific and Australian crustal plates, is characterized by a dynamic, active landscape – mountainous and hilly regions with steep slopes cover large areas of the country, and uplifted and dissected sedimentary and volcanic rocks with low strength properties are widespread. However, New Zealand's location in the southwestern Pacific means that sub-tropical cyclones hit the land mass of New Zealand on a regular basis, creating heavy rainfall in the affected areas. Settlement history has seen major shifts in land use and land coverage, beginning with Maori settlement several centuries ago and continuing with European settlement. Large land areas have been cleared of indigenous forest and converted into crop land and pasture, exposing weak parent material to the actions of weather and climate. These factors contribute to the pronounced erosion susceptibility of New Zealand landscapes. In particular, the North Island of New Zealand is affected by high rainfall events triggering widespread erosion in shallow soils – especially if they are exposed, such as in pastoral areas. New Zealand's coastal estuaries are sensitive to the related increases in sediment loads from terrestrial sources. Management of these inputs and the associated risks to the estuarine biota requires a sound understanding of the effects of land use, soil, topography, and climate on sediment generation. In this study the detailed physically-based model SHETRAN was applied and tested for the Waitetuna catchment of the Raglan Harbour/Whaingaroa (170 km^2), with the aim of representing signals in terrestrial sediment generation. We conducted intensive monitoring of streamflow, turbidity and transported sediment under intensive rainfall conditions for several key locations around the catchment. The outputs of the model are provided to separate models for routing flow and sediment down the main-stem and sediment dispersion in the estuary. We used model scenarios for different land-use scenarios to explore land-use impacts on sediment generation and to suggest catchment management alternatives to minimize erosion impacts on the Raglan estuary.

STUDY AREA AND DATA

An extensive monitoring programme was conducted in the Waitetuna catchment and estuary (Fig. 1) to capture data from the catchment, stream and estuary simultaneously. Water-level recording sites were established within the Waitetuna catchment with the aim of capturing flood events and estimating the fine sediment loads by using turbidity as a surrogate for suspended sediment concentration. Six small catchment sites were established in the Waitetuna catchment in August 2005. The sites cover a range of land uses and catchment sizes varying from 0.91 to 2.70 km^2. Five water-level recorder sites on the Waitetuna River main-stem and one on the neighbouring

Mangakino Stream measured streamflows between March 2005 and September 2006. Water levels were sensed at 5-min intervals by pressure transducers (Unidata Starflow) at the catchment sites and at 15-min intervals by floats in stilling wells at the stream sites. Water levels were converted to flow using stage to discharge relationships based on gaugings. Turbidity was monitored at 5-min/15-min intervals with OBS3 turbidity sensors (D & A Instrument Company). The OBS3 is an optical sensor for measuring turbidity by detecting near infrared radiation back-scattered from suspended particles. Automatic samplers (Manning models 4900, GLI and ISCO models 3700, 6700, 6712) were installed at all sites and were triggered using a pager. Samples were taken at 30-min intervals for the first 12 h, and then hourly at catchment sites, and hourly at stream sites. All samples were analysed for turbidity with a Hach nephelometer (2100 AN) and gravimetrically. A monitored flood event started on 24 January 2006 and had two discrete rainfall events. The first rainfall was associated with a NE airflow and resulted in 55.5 mm in the lower Waitetuna catchment over a 14 h period. The second event was an intense storm with 66.5 mm of rain fell in 7 h, with a maximum intensity of 17.5 mm/15 min. Data for each site were examined to see if relationships existed for the different parts of the hydrograph, e.g. the rising or falling limbs of each of the two flood peaks. Linear regression models were developed between independent variables (flow, OBS turbidity, lab turbidity) and suspended sediment concentration.

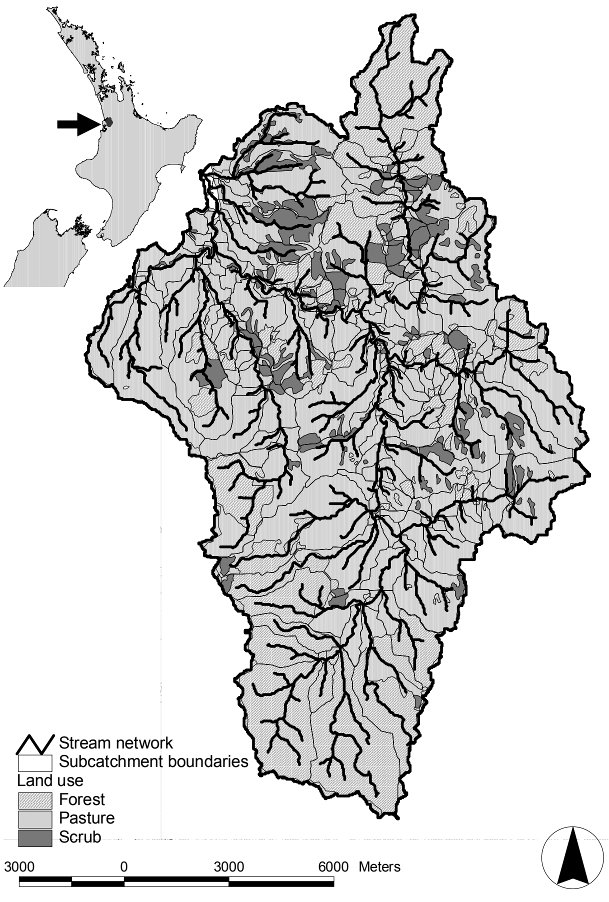

Fig. 1 Waitetuna catchment in the Raglan Harbour, North Island, New Zealand; current land-use and subcatchment boundaries used in this study.

METHODOLOGY

SHETRAN is a physically-based, spatially distributed model of hydrological cycle within catchments, including sediment and contaminant transport (Ewen *et al.*, 2000). The model is based on the Système Hydrologique Européenne (SHE) hydrological modelling system, developed by the Danish Hydraulic Institute (DHI), the Institute of Hydrology (UK), and SOGREAH (France), and modified substantially by the University of Newcastle upon Tyne (Bathurst *et al*., 1995). SHETRAN has been applied and validated successfully for various areas around the globe in different climatic regions, including India, Idaho (USA), Portugal, UK, Ireland and Spain (Bathurst *et al*., 1995, 2006). In previous studies we applied SHETRAN to a small study area close to the Waitetuna catchment of this study (Adams & Elliott, 2006) – providing ideal conditions to apply and upscale the experiences gained by those studies.

To apply a sophisticated high-resolution model like SHETRAN to a catchment of 170 km^2, we designed the following modelling strategy. We did not follow the method of increasing grid cell size as this has been done in other studies (e.g. Bathurst *et al*., 1995) which leads to problems of oversimplification of catchment topography, soils, and land use. We subdivided the catchment into subcatchments and created SHETRAN models for all subcatchments in high grid resolution. The number of subcatchments was chosen so that number of grid cells in each subcatchment was small enough for reasonable computational times and data storage requirements. The process of generating SHETRAN subcatchment models was completely automated so that the models can be set up directly from a GIS database of topography (DEM, channel network, catchment boundaries), soils (soil units), land cover units, and a repository of SHETRAN model parameters, which are linked to the soil and land cover units (Fig. 2).

For the Waitetuna catchment, a DEM of grid size of 20-m grid cells was maintained in order to represent topographic detail. Stream lines were delineated so that they match the DEM topology and real-world streams in the catchment. A D4 flowpath algorithm (see e.g. Tarboton, 1997) was used to ensure the delineated network matches SHETRAN requirements (no diagonal flow). The network was used to delineate the corresponding subcatchment boundaries; these were then aggregated manually into a set of subcatchments of appropriate number and sizes; for the Waitetuna catchment of a size of 170 km^2; we delineated about 200 subcatchments (see Fig. 1). Soil units were derived from the New Zealand Land Resource Inventory (LRI) (Newsome *et al*., 2000). Land cover units were derived from the New Zealand land cover database (LCDB). The SHETRAN model parameters were derived primary from field data, or where data were not available, the parameters were assessed from expert knowledge or standard SHETRAN parameters. These model parameters were linked to the LRI soil units or LCDB land cover units, so that for each modelled grid cell the appropriate model parameters can be transferred to the SHETRAN modelling system. The process of generating the SHETRAN models was then done by a series of automated scripts by querying the GIS database and converting the information into SHETRAN input files for all the subcatchments. When SHETRAN is run on all the subcatchments, discharge and sediment (different particle sizes) concentration timeseries can be modelled by the SHETRAN modelling system for the subcatchment outlet (which always is a stream element). These time series can be then provided to the stream model which carries out hydraulic routing of water and sediment through the entire stream network of the Waitetuna catchment.

MODEL APPLICATION AND DISCUSSION

SHETRAN was setup for current land-use conditions and for the measured storm events on 24 January 2006, as mentioned above, to simulate event streamflows and event sediment yields for each of the delineated 200 subcatchments (Fig. 1). Calibration and validation was carried out for the subcatchments where measured streamflows and sediment yields were available. The model runs highlight the diverse patterns of runoff and sediment generation over the Waitetuna catchment, which are dependent on spatial rainfall pattern, topography, land use and soil parameters. For the simulated event, high sediment yields were derived for the northern and southern subcatchments (Fig. 3), which received high event rainfall intensities and have higher slope gradients, but are not under pasture. Understanding these patterns is important for catchment management strategies to reduce sediment generation on the land and therefore sediment input in the estuary.

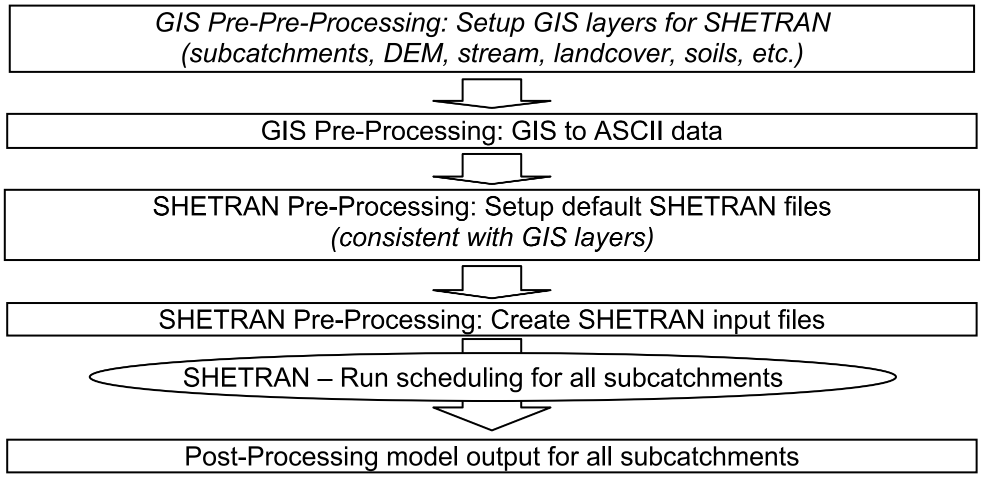

Fig. 2 GIS / SHETRAN integration for automatically generating SHETRAN models.

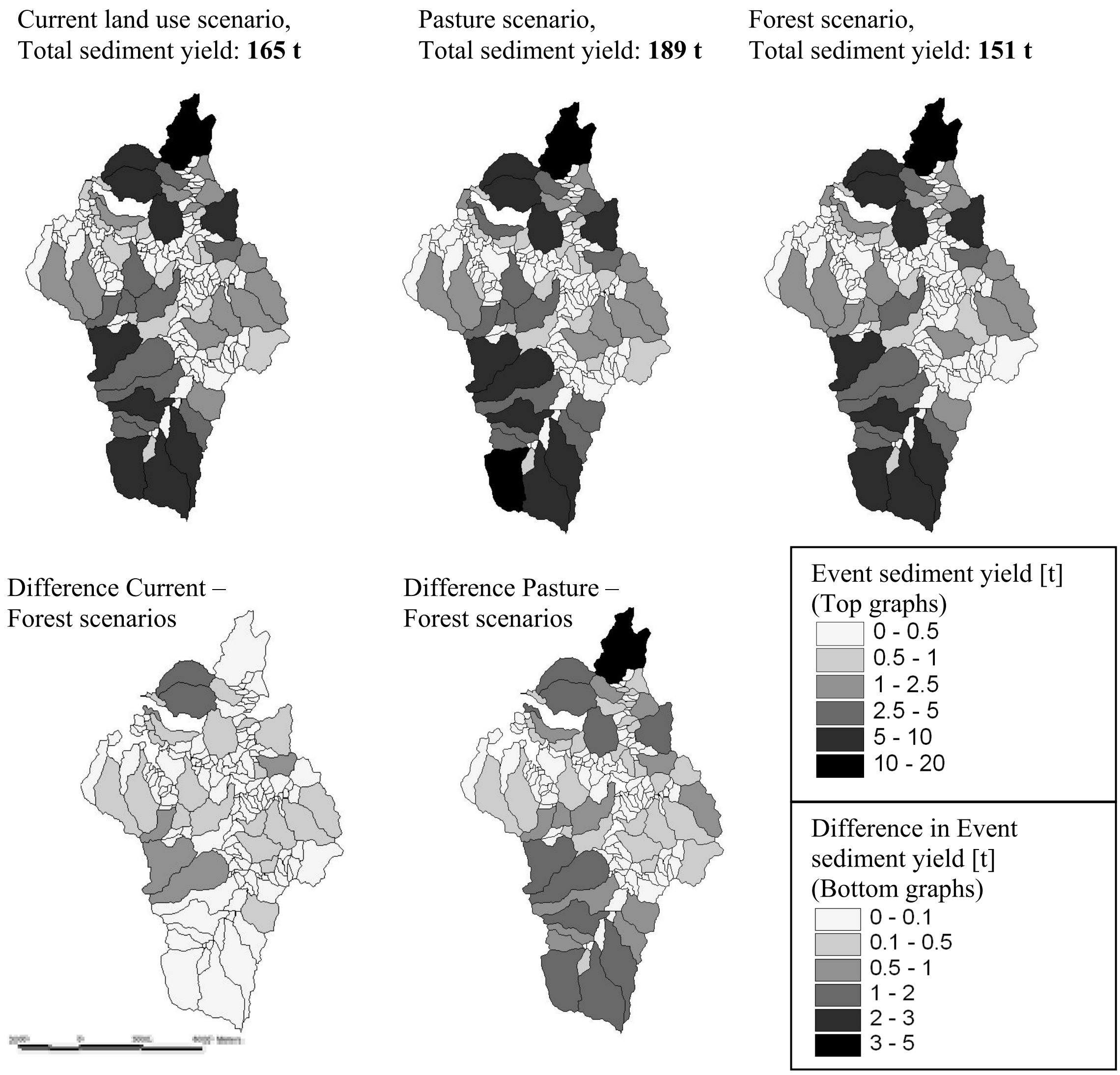

Fig. 3 Model results showing the impact of different land-use scenarios on simulated event fine sediment yields for the 24 January 2006 event for each subcatchment (top graphs). Bottom graphs show the difference of the sediment yield for the simulated scenarios.

Finally, the land use was changed in two scenarios to simulate subcatchment event runoff and sediment yield for situations where the whole Waitetuna catchment is: (1) completely under pasture, and (2) completely converted back to native forest. The simulated event sediment yields (Fig. 3) were compared for the three scenarios and indicate, as expected, significantly reduced runoff (not shown) and sediment yield for the native forest scenario. The simulation results show that the total event fine sediment yield for the whole Waitetuna catchment would be reduced by 24 t and 38 t under the forested scenario compared to the current land-use and the pasture scenario, respectively. The spatial pattern of event sediment response from different subcatchments for the "current" and "native" land-use scenarios indicates areas where management and land-use conversion to native forest could have the biggest impact on the overall catchment sediment yield. The spatial pattern of event sediment response from different subcatchments for the "pasture" land-use scenario indicate areas where conversion to pasture could have the biggest adverse impacts on total catchment sediment yield. The results show that the current forested headwater catchments in the north and south ends of the Waitetuna catchment have the highest potential for adverse impacts resulting from land-use change to pasture, and hence, should remain under native forest.

A spatially distributed, physically-based model like SHETRAN can be used as a framework to provide scenarios of event sediment yields for a larger catchment. We are currently working towards relating the spatial pattern in catchment event sediment yield to event characteristics, e.g. rainfall intensity and duration, and spatial rainfall pattern, to understand how event sediment response in the Waitetuna catchment scales over ensembles of events, and finally, over longer time scales. The ultimate goal is to develop a model of catchment sediment generation from event scales to decadal scales, which can be applied in designing appropriate sustainable land-use strategies on multiple temporal scales.

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