Water Resour Manage
DOI 10.1007/s11269-008-9268-2

Modelling Impacts of Land Cover Change on Critical Water Resources in the Motueka River Catchment, New Zealand

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Received: 25 January 2007 / Accepted: 6 March 2008

Abstract After the SWAT (Soil and Water Assessment Tool) model was calibrated and validated to historic flow records for the current land use conditions, two additional land cover scenarios (a prehistoric land cover and a potential maximum plantation pine cover) were used to evaluate the impacts of land cover change on total water yields, groundwater flow, and quick flow in the Motueka River catchment, New Zealand. Low-flow characteristics and their potential impacts on availability for water abstraction and for support of in-stream habitat values were focused on. The results showed that the annual total water yields, quick flow and baseflow decreased moderately in the two scenarios when compared with the current actual land use. The annual water balance for the pine potential land cover scenario did not differ substantially from the prehistoric scenario for the catchment as whole. However, there were more notable differences among individual tributary catchments, which could be attributed to the relative area of land cover altered and location of those catchments. Simulated low flows for the prehistoric and potential pine land cover scenarios were both significantly lower than the low flows for the current land use. In summary, under the current land use conditions, both annual water yield and low flow are higher than was the case before human intervention in the area or in a maximum commercial reforestation scenario.

Keywords Land use/cover change · Hydrological impacts · Soil water assessment tool · Low flow

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1 Introduction

1.1 Water Yield Impacts of Land Cover Change

Land cover and land use have dramatically changed since Polynesians and Europeans settled in New Zealand. The indigenous forest cover of New Zealand has been reduced from an estimate of approximately 85% of the land area to about 23% (Statistics New Zealand 2002). Changes in land use occur continuously in response to population growth and changes in the primary production activities that are vital to New Zealand's overall economy. In some areas, the removal of farm subsidies since the mid-1980s has led to land reverting back to scrub and native forest, in others agricultural intensification has led to new areas of irrigated pasture and crops.

Land cover and land use changes alter the hydrological cycle of a catchment by modifying rainfall, evaporation, and runoff, particularly in small catchments. Fahey and Rowe (1992) provide a review of hydrological consequences of land use change in New Zealand, while Rowe et al. (1997) focused on land use change impacts on extreme flows. The impacts of a variety of land use alterations including major conversions (indigenous forest to pasture, tussock grassland to pasture, and indigenous forest to pine plantation) and minor conversions (tussock grassland to pines, pastures to pines) on both quickflow and delayed flow have been summarized in these reviews. Generally, the removal of forest or scrub and its replacement with pasture will increase annual water yields; a similar increase can also be observed when native forest is replaced by pines in medium-to-high rainfall areas, although with time the water yields become similar. When *Pinus radiata* and *Pinus contorta* are planted in tussock grassland, annual water yields will decrease. For pasture lands planted with *P. radiata* annual water yields are reduced (Fahey and Rowe 1992; Rowe et al. 1997). However, most of these research results derive from previous experiments on the hydrological impacts of individual land use changes in small catchments, using "paired-catchment" or "multiple-catchment" approaches. In these studies, low flow characteristics were often neglected, because the early focus of water management was primarily on flood protection and soil conservation (Fenemor 1992). However, attention has now shifted to regional water management issues in meso- to macro-scale river catchments, where environmental heterogeneity is high, patterns of land use and land use change are complex, and environmental impacts affect a variety of resources simultaneously. Under these circumstances the nature and magnitude of changes to land use and land cover on surface runoff generation and low flow characteristics are uncertain.

This paper reports a model "soil and water assessment tool (SWAT)" simulations in the New Zealand context for evaluating how two different land use/land cover scenarios would affect annual water yield and low-flows, compared to the current conditions in a large, heterogeneous river catchment: the Motueka River catchment in New Zealand.

1.2 The Motueka Catchment

The Motueka river catchment is situated at the northern end of the South Island of New Zealand. The river drains an area of 2,180 km^2 and has a main stem length of about 110 km. It provides roughly two thirds of the freshwater flow into Tasman Bay. The elevation of the two primary tributaries (the Motueka and Wangapeka) is roughly 1,600 m. Two thirds of the catchment is steep country with slopes exceeding 15°. Mountainous headwaters open out into wider valleys of moderate to rolling contour (Basher 2003).

Water is a critical resource in the seasonally-dry Motueka River catchment. Over much of the catchment, demand for water is generated by abstractions from both surface and ground water and indirectly by shifts in land cover, principally by increasing afforestation with *P. radiata* pine. In the summer months demand may exceed supply. This competition results in conflicts among multiple groups, specifically among terrestrially based production sectors (e.g. forestry and irrigated horticulture), with freshwater users (e.g. trout fishing and river recreation), and potentially with coastal users (e.g. fisheries, aquaculture industries). The major concerns include the degradation of groundwater and surface water from land-use; degradation of coastal water quality; and allocation among these sectors of scarce water resources. It is necessary to take an integrated approach to address those multi-faceted issues. To this end, the Motueka River and Tasman Bay "Integrated Catchment Management" programme was launched in 2000, to promote adaptive management that focuses on biophysical, economic, and community factors associated with water management in the Motueka Catchment. The SWAT model was identified as tool that might be especially helpful as a means to summarize the complex dynamics and issues in this area.

1.3 Model Description

SWAT is a physically based, distributed, hydrological model that operates on a daily time-step, and can be used to predict the impacts of land management practices on water, sediment and agricultural chemicals in catchments (e.g. Fohrer et al. 2001; Chaplot et al. 2004). A catchment is first split into sub-basins according to the terrain and river channels, and then into multiple hydrological response units (HRUs) based on the soil and land cover types within the sub-basins. An HRU is a fundamental spatial unit upon which SWAT simulates the water balance (Arnold et al. 1998). Briefly, the hydrological processes modelled in SWAT are precipitation, surface runoff, soil and root-zone infiltration, evapotranspiration and soil and snow evaporation, and baseflow. Comprehensive descriptions of SWAT can be found among other places (e.g. Arnold and Allen1996; Arnold et al. 1998; Srinivasan et al. 1998), and the local detailed parameterization, such as precipitation and temperature input, evapotranspiration computation, and runoff estimate, can be found in the previous study (Cao et al. 2006).

2 Application of SWAT

2.1 Land Use and Land Cover Change Scenarios

The Motueka Catchment was originally almost entirely forested with podocarp species in the fertile lowland areas and several different southern-hemisphere beech (*Nothofagus*) species elsewhere (Walls 1985). Present land use in the Motueka Catchment comprises exotic forestry, covering 25% of catchment area, followed by sheep and beef farming (19%), and limited but increasing dairy farming (Fig. 1). Horticulture (mainly pip fruit, berry fruit, hops, vegetables) occupies a small, but expanding, area mainly situated along river terraces and alluvial plains and is a major water user. Most crops are irrigated from surface or groundwater during the summer. A large area of the catchment (55%), mainly in the high rainfall headwaters of the western tributaries and upper Motueka is conservation land covered predominantly by land cover types such as forest, scrub and tussock grassland.

The New Zealand Land Cover Data Base (LCDB), a digital thematic map of land cover for use in a geographic information system (Ministry for Environment 2000), was used to

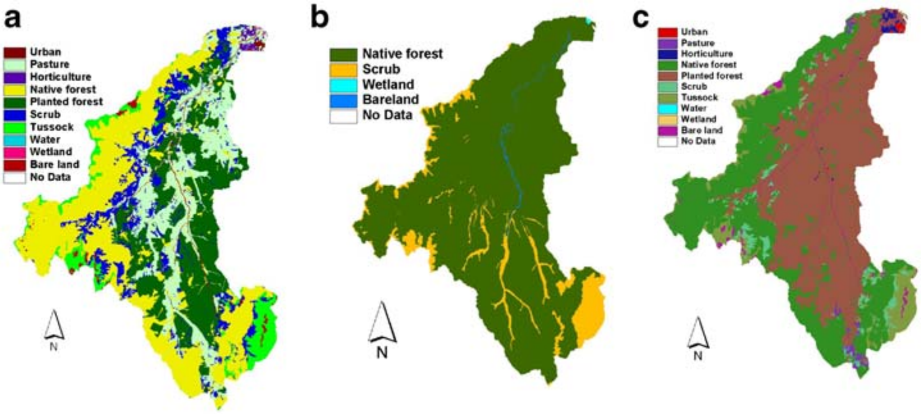


Fig. 1 The current land cover and two land cover scenarios. **a** Current land cover. **b** Prehistoric scenario. **c** Potential pine plantation scenario

define land uses in the Motueka Catchment (Table 1). The data in the LCDB was derived from Spot II satellite imagery acquired in summer of 1996/1997 and described 16 land use/cover classes. Overall classification accuracy is 93%, although this varies between cover classes. The satellite images have a 20-m spatial resolution, and the minimum mapping unit is 1 ha (Ministry for Environment 2000).

Two additional land cover scenarios—a prehistoric land cover and a potential maximum plantation pine cover (Leathwick 2001)—were used to evaluate the impacts of land cover change on water resources. The prehistoric land cover described conditions prior to either Maori or European alterations to the landscape and was compiled initially based on expert knowledge of the likely vegetation in a pre-human condition. This initial land cover was then further refined using an additional climate layer. The upper elevation limit of forest or tree lines was derived from studies of the correlation between summer temperature and tree line. The land cover scenario was taken from the Land Environment New Zealand classification (Leathwick et al. 2002), and consisted of 87.94% original indigenous forest

Table 1 Current land use and land cover scenarios

Land use	Prehistoric land cover		Current land cover		Potential pine plantation	
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Urban land	–	–	0.2	0.01	0.2	0.01
Pasture	–	–	326.2	17.90	15.3	0.84
Horticulture	–	–	0.9	0.05	0.9	0.05
Indigenous forest	1,602.2	87.94	671.3	36.84	671.0	36.83
Planted forest	–	–	484.8	26.61	913.4	50.13
Scrub	213.5	11.72	180.7	9.92	63.6	3.49
Tussock	–	–	133.5	7.33	132.3	7.26
Water	–	–	0.1	0.01	0.1	0.01
Bare land	5.9	0.33	24.7	1.35	24.7	1.36
Total[a]	1,822.0	100.00	1,822.0	100.0	1,822.0	100.0

[a] The area is delineated and generated by the model interface and bigger than the Motueka Catchment down to Woodstock (Fig. 1)

and 11.72% scrub plus 0.33% bare land. This land cover is considered as a prehistorically original land cover, which had no anthropogenic disturbance at all.

The maximum plantation pine cover scenario described a condition in which plantations of *P. radiata* occupied the maximum conceivable area in the Motueka River catchment. Multiple factors were used to define the potential maximum extent of plantation pine cover, including growth potential, weed type and incidence, logging and roading costs, extreme climate risks, fire, pest risks and social constraints (Leathwick 2001).

Land cover types from current, prehistoric, and potential maximum plantation pine cover scenarios (Fig. 1) were regrouped into generic land cover types for use in SWAT. No new land cover type was introduced in the two land cover scenarios compared with the "current" (Table 1 and Fig. 1).

2.2 Subcatchments and Precipitation

The 407 subcatchments and 902 hydrological response units were generated in reflect to high heterogeneity in geology, geomorphology, and land uses in the Motueka river catchment. These subcatchments were regrouped into seven tributary catchments due mainly to availability of flow measurement locations within the catchment (Fig. 2 and Table 2). The SWAT model was calibrated and validated for each of the seven tributary catchments (Table 3).

Fig. 2 The Motueka catchment and its tributary catchments

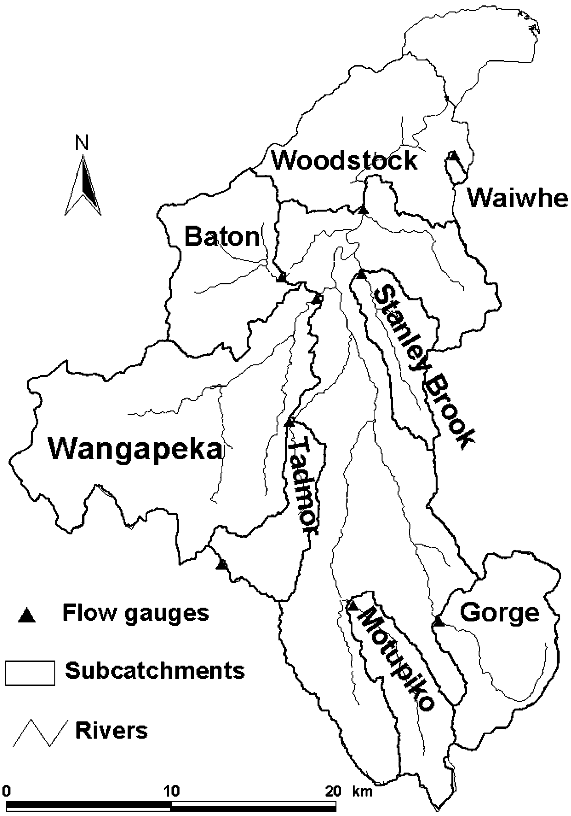


Table 2 The Motueka catchment and tributary catchments

Tributary catchments (Flow gauge name)	Area (km^2)	Area (%)
Baton (Baton Flats)	168.0	9.6
Upper Motueka (Gorge)	163.0	9.3
Stanley Brook (Barkers)	81.6	4.7
Tadmor (Mudstone)	88.0	5.0
Wangapeka (Walters Peak)	479.0	27.4
Motupiko (Christies)	105.4	6.0
Motueka (Woodstock)	1,765.6	100.0

The Woodstock flow gauge provides the final measurement for the catchment although there is still about 450 km^2 below this point; area (%) in 3rd column is an area percentage of the Motueka at Woodstock

A separate pre-processing model had been used to predict the daily precipitation based on the gauges and other information, and the daily precipitation predictions for the model use have been effectively verified using other rain data set (Cao et al. 2006). Therefore, no elevation band was used for the model application.

2.3 Groundwater and Irrigation

Groundwater is mainly distributed in the floodplain and fans of the Motueka Plains near the coast, and the terraces and floodplains in the upper Motueka. The groundwater system in the Motueka Plains has been investigated and well documented (Robb 1990; TDC 1995). A baseflow recession constant, derived from daily stream flow records is used in SWAT to characterize the stream behaviour and water yields, and to lag flow from the aquifer to the stream. The value of baseflow recession constant ranges from 0 to 1, but the value usually lies between 0.500 to 1.000 in New Zealand. The specific value for the baseflow recession constant of each tributary catchment was determined from flow records using recession days and their corresponding recession constant as proposed by Martin (1973).

Irrigation data derived from a database in which user names, geographical locations, water consumption, area, and sources (groundwater or surface water) were recorded by

Table 3 Calibration and validation results

Tributary	Periods	Nash–Sutcliffe coefficient	R^2
Baton	Calibration	0.36	0.60
	Validation	0.35	0.51
Upper Motueka at Gorge	Calibration	0.42	0.52
	Validation	0.41	0.41
Stanley Brook	Calibration	0.59	0.65
	Validation	No records available for validation	
Tadmor	Calibration	0.61	0.61
	Validation	0.55	0.56
Wangapeka	Calibration	0.60	0.62
	Validation	0.51	0.53
Motupiko	Calibration	0.40	0.54
	Validation	0.57	0.61
Motueka at Woodstock	Calibration	0.78	0.82
	Validation	0.72	0.75

local government. Irrigation was applied in the model simulations for the current land use only, owing to the assuming conversions from pasture to planted pine forest for the maximum plantation pine cover scenario.

3 Results and Discussions

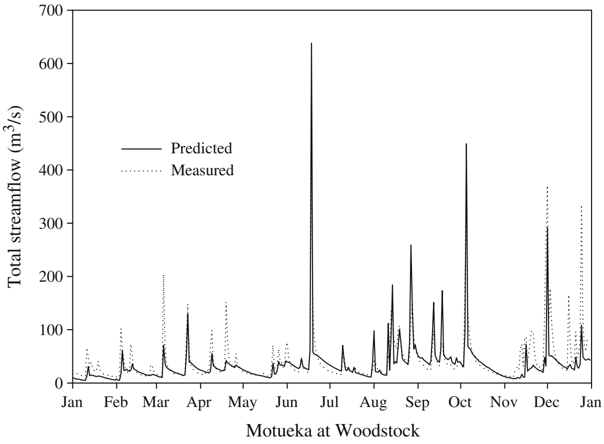
3.1 Calibrations and Validation

A multi-variable and multi-site approach had been used to calibrating SWAT model internal state variables, such as evapotranspiration and baseflow (multi-variables), and the calibrations were conducted in several tributary catchments (multi-sites) through a trial-and-error process. The method used extensive field measurements from various time scales in different catchments for model calibration and validation, and it has been suggested as an effective methodology for reducing uncertainty in parameterization (Cao et al. 2006).

The calibration and validation were completed using the flow records from 1990 through 2000. The period was split into two periods: 1990–1994 for calibration and 1995–2000 for validation. The R^2 value for simulated versus observed daily streamflow from the whole catchment (at Woodstock) was 0.82 for the calibration period (1990–1994) and 0.75 for the validation period (1995–2000). The R^2 for simulated versus observed streamflow was greater than 0.5 for all of the tributary catchments except the Upper Motueka at the Gorge during the validation period. In addition to simple R^2 values, the Nash–Sutcliffe "goodness of fit" coefficient (Nash and Sutcliffe 1970) was used to evaluate the calibrated model performance. The Nash–Sutcliffe coefficient ranges from 1 for a perfect fit to 0 for a complete absence of fit. The final calibration at the Woodstock (whole catchment) station for daily streamflow yielded a Nash–Sutcliffe coefficient of 0.78; the coefficient ranged from 0.36 to 0.61 for the individual tributary catchments (Table 3). For the validation dataset (1995–2000), the Nash–Sutcliffe coefficient was 0.72 for the whole catchment and ranged from 0.35 to 0.57 for the tributary catchments.

The simulated annual total streamflow for the entire catchment (at Woodstock) agreed reasonably well with measured values (Fig. 3). However, the model agreement was variable in the tributary catchments. The agreement was generally good for the Wangapeka, Tadmor and Stanley Brook tributary catchments. However, the model performed somewhat poorly

Fig. 3 Simulated daily streamflow against the measured at Woodstock in 1997



in other parts of the catchment, such as the Baton and upper Motueka at Gorge. The SWAT model seemed to perform well for the whole catchment at Woodstock because the biases from predictions from the individual tributary catchments tended to offset and compensate each other (Moriasi et al. 2007).

The R^2 for the predicted annual baseflow against the hydrograph-separated annual mean baseflow for the 11 years of record at Woodstock was 0.79 (Fig. 4). This acceptable agreement between the SWAT predictions and the measured base flow values suggests that the SWAT model can be used to evaluate seasonal low flow events.

3.2 Land Use/Cover Changes

Comparisons showed that, since human activities began, 931 km^2 (58.11%) of indigenous forest and 33 km^2 (15.46%) of scrub were removed and replaced by current pasture, planted forest and horticulture. The major changes that would occur if current land use evolved to the maximum potential pine plantation scenario would be conversions from pasture to planted pine forest (310-km^2), and from scrub to planted pine forest (117-km^2) (Table 1). Other land use and land covers (principally the conservation estate and urban areas) would remain largely unaltered.

Compared with current land cover, the proportions of forest are greater in both the prehistoric and future maximum pine scenarios. For the prehistoric scenario, the land cover is about 99% forest with 87% in native forest and 12% in scrub. For the maximum pine scenario the land cover is about 89% forest, with 37% in native forest, 50% in pine forest, and 3% in scrub (Table 4). The pasture is absent in both the prehistoric and future maximum pine scenarios. Changes in land use and land cover are proportionately greatest in the Motupiko, Tadmor, Wangapeka and Stanley Brook catchments because they are the catchments with the highest proportions of production land uses currently (Table 4). In each of the tributary catchments there were multiple land cover changes and complex patterns of land cover change in both scenarios.

Fig. 4 The predicted against the hydrograph separated annual mean baseflow over 11 years at Woodstock

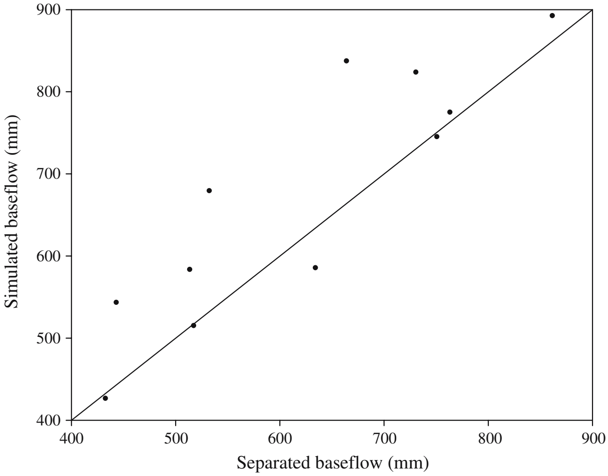


Table 4 Land cover and percentage change from current land cover for the 2 scenarios

Land cover	Baton		Upper Motueka at Gorge		Stanley Brook		Tadmor		Wangapeka		Motupiko	
	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
Prehistoric (km^2)												
Pasture					0	−20	0	−20	0	−45	0	−31
Native forest	153	+29	80	+3	82	+80	80	+54	425	+173	97	+66
Planted forest	0	−1	0	0	0	−58	0	−33	0	−55	0	−31
Scrub	22	+5	87	+67	0	−2	10	0	46	−27	7	−2
Tussock	0	−23	0	−66					0	−38	0	−1
Bare land	0	−2	0	−4					0	−8		
Potential pine plantation (km^2)												
Pasture	0	−7				−20	0	−20	1	−45	13	−18
Native forest	124	0	76	0	2	0	25	0	251	0	31	0
Planted forest	23	+22	2	+1	79	+22	62	+29	145	+91	51	+20
Scrub	2	−15	18	−1		−2	2	−9	27	−45	7	−2
Tussock	23	0	66	0			0	0	37	−1	1	0
Bare land	2	0	4	0			0	0	8	0	0	0

3.3 Hydrological Response to the Land Use/Cover Change

The prehistoric land cover scenario represents an original land cover with no anthropogenic disturbance, whereas, the potential maximum pine plantation represents one extreme consequence of economic expansion. Each scenario was simulated on a daily basis, and an annual mean was summarized over an 11-year period from 1990 through 2000.

3.3.1 Evapotranspiration

Annual actual evapotranspiration (ET) was greatest for the prehistoric scenario at Woodstock, followed by the pine potential, and then current land use. For the Motueka at Woodstock, an average of 705 mm water was evapotranspired under the prehistoric conditions, 694 mm under the maximum pine potential conditions, and 656 mm under current land use (Table 5). Compared with the current land use, the prehistoric land cover increased mean annual ET by 7.5% for the whole catchment to Woodstock, while the pine potential scenario increased it by 5.9% (Table 6). The ET changes were not evenly

Table 5 Water balances of the current land uses for the Motueka catchment

Water balance	Tributary catchments						Whole
	Baton	Upper Motueka at Gorge	Stanley Brook	Tadmor	Wangapeka	Motupiko	Woodstock
Precipitation (mm)	2,355	1,603	1,210	1,602	2,283	1,375	1,730
Snowmelt (mm)	35	98	0	13	24	12	21
Mean ET (mm)	670	595	646	680	688	642	656
Surface runoff (mm)	524	379	40	106	396	128	219
Subsurface lateral flow (mm)	46	37	51	66	83	39	65
Groundwater flow (mm)	989	588	366	641	980	507	677

Table 6 Mean water balance changes at different catchments compared to the current

Scenarios	Tributary catchments						Whole
	Baton	Upper Motueka at Gorge	Stanley Brook	Tadmor	Wangapeka	Motupiko	Woodstock
Mean ET changes (%)							
Prehistoric	+4.0	+12.4	+7.3	+9.5	+4.9	+10.3	+7.5
Potential pine	+1.4	+2.1	+7.0	+9.8	+3.1	+9.2	+5.9
Total water yields changes (%)							
Prehistoric	−1.4	−8.2	−12.5	−8.9	−2.4	−10.8	−5.5
Potential pine	−0.7	−1.9	−12.1	−9.3	−1.6	−9.6	−4.5
Quick flow changes (surface runoff + subsurface lateral flow) (%)							
Prehistoric	−2.3	−10.6	−19.5	−14.1	−5.5	−15.7	−7.7
Potential pine	−0.3	−0.6	−13.1	−9.7	−1.9	−7.6	−3.4
Baseflow changes (%)							
Prehistoric	−0.5	−5.0	−10.1	−7.3	−0.7	−8.6	−3.9
Potential pine	−0.7	−2.0	−11.9	−8.9	−1.1	−9.7	−4.5

distributed among the tributary catchments. Higher ET changes (>+5%) were predicted to occur in Stanley Brook, Tadmor, Motupiko catchments under both the prehistoric and the pine potential scenarios, and in the upper Motueka at Gorge catchment under the prehistoric scenario (Table 6). In the Wangapeka catchment, the annual mean ET increment was only 4.9% and 3.1% under the prehistoric and the pine potential, respectively. Tadmor was the only catchment where the mean annual ET from the prehistoric was less than that from the pine potential. These changes reflect the proportion of each catchment suited to prehistoric vegetation cover versus pine conversion.

3.3.2 Total Water Yields

Total annual water yield was 5.5% less at Woodstock under the prehistoric land cover and 4.5% less for the pine potential scenario (Table 6). The decrease in total water yield was approximately 10% for the Stanley Brook, Motupiko, and Tadmor catchments. Annual water yield was reduced by 12.5%, 10.8% and 8.9% under the prehistoric conditions and by 12.1%, 9.6% and 9.3% under the pine potential conditions, respectively. Annual water yield decreased by less than 3% in the Wangapeka and Baton catchments in both scenarios and for the maximum pine scenario in the Upper Motueka at Gorge catchments. This occurred because a large proportion of these headwaters is forested under current land use.

3.3.3 Quick Flow and Baseflow

The quick flow (surface runoff + subsurface lateral flow) was substantially changed in some tributary catchments. Quick flow decreased by 19.5% and 13.1% under the prehistoric and the pine potential respectively in the Stanley Brook catchment. However, at Woodstock, the quick flow was reduced only 7.7% and 3.4%, respectively. In comparison, baseflow was reduced less under the prehistoric land cover than for the pine potential, except catchment upper Motueka at Gorge. Substantial decreases in baseflow occurred in the Stanley Brook, Motupiko, and Tadmor catchments.

The current land cover generally had the highest daily streamflow, followed by the maximum pine potential scenario and then the prehistoric land cover scenario. The relative hydrologic changes over the entire Motueka Catchment were modest (<8%). However, at the more fine scale of tributary catchments—in particular the Stanley Brook, Motupiko, and Tadmor catchments—the relative changes in water resources could be larger and might pose some concern with respect to meeting irrigation needs and protection in-stream values. Although, relative hydrologic changes in Wangapeka and Baton catchments were moderate, the absolute magnitude of change was high for these tributary catchments because they have large catchment areas and higher levels of mean annual precipitation than the other watersheds (Tables 5 and 6).

In the Stanley Brook, Tadmor, and Motupiko catchments, increases in forest cover in the prehistoric and maximum pine scenarios caused substantial increases in ET and decreases in water yields, quick flow and baseflow. In the Wangapeka, the major land cover conversions were between native forest and planted forest, and a significant proportion of native forest for conservation purposes remains in current land cover. Moreover, high annual precipitation occurs in the Wangapeka so the higher evaporation rate by forest is relatively compensated in tributary catchments (Tables 5 and 6).

Land use/cover change impacts on water resources are complex, but typically moderate as catchment area increases. Afforestation typically alters the water cycle through increased interception, increased transpiration, and decreased soil moisture (Bosch and Hewlett 1982; Calder 1992). Conservation forest (indigenous forest) occupies a large area mainly in the high rainfall headwaters of the western tributaries and upper Motueka and remained unaltered in both of the simulation scenarios. The potential pine plantation is mainly in the dry central valley and eastern hill country. The hydrological impacts from the potential pine scenario on total water yields and quick flow were little different from those caused by the prehistoric scenario. The changes in water balances depend upon a combination of factors, including the geographical areas altered, type of forest vegetation, and climate of the area (Bosch and Hewlett 1982; Calder 1992).

3.4 Low Flows Response to Land Cover Change

Low flow occurs during the dry season of the year or between storm events, especially when there are long intervals between these events (Smakhtin 2001). Flow duration curves (FDC) for the current and two alternative land cover scenarios (Fig. 5) indicate that there

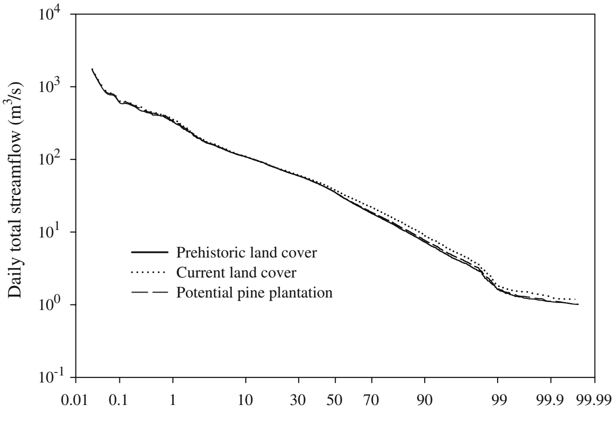


Fig. 5 Flow duration curves for Motueka river at Woodstock for the three land covers

are small but important departures in low flows (those equalled or exceeded 50% of the time) between the current condition and both of the hypothetical scenarios. Low flows were substantially lower for both the prehistoric and pine potential land covers compared to the current land cover (Table 7). Streamflow for flow conditions in the 70–99 flow percentiles were lower by 10% or more. Low flows were lowest for the prehistoric scenario (Table 7). In some tributary catchments (Motupiko, Stanley Brook, and Tadmor) the decrease in low flows in the 50–99 percentiles was 40% or more for both alternative land cover scenarios. In Stanley Brook where the predominant lithology is impervious Moutere Gravels, low flows in the 70–90 percentiles decreased approximately 69% for both alternative land cover scenarios. This large decrease can be attributed to the low water storage characteristics of soils in the tributary catchment and the expected effects of afforestation on low flows during summer soil moisture deficits. This result is consistent with the empirical results reported by Duncan (1995) for five small catchments (4.0–7.7 ha) on Moutere Gravels where, over a 6-year period, low flows were reduced by more than 50% by afforestation with plantation pine.

Table 7 Total streamflow (m^3/s) and streamflow change (%) for various percentages of time that flow is equalled or exceeded for subcatchments

Land cover	99%		95%		90%		70%		50%	
	m^3/s	%	m^3/s	%	m^3/s	%	m^3/s	%	m^3/s	%
Motueka at Woodstock										
Prehistoric	1.66	−17.4	4.65	−20.0	7.26	−19.7	18.12	−17.3	35.29	−6.4
Current	2.01	0	5.81	0	9.04	0	21.92	0	37.70	0
Pine potential	1.75	−12.9	4.97	−14.5	7.77	−14.0	18.65	−14.9	35.33	−6.3
Baton										
Prehistoric	0.192	−2.0	0.728	−15.1	1.358	−8.7	3.661	−4.0	5.812	−1.6
Current	0.196	0	0.857	0	1.487	0	3.814	0	5.909	0
Pine potential	0.194	−1.0	0.804	−6.2	1.420	−4.5	3.727	−2.3	5.846	−1.1
Upper Motueka at Gorge										
Prehistoric	0.127	−15.3	0.238	−30.6	0.371	−35.0	1.330	−25.9	2.846	−11.6
Current	0.150	0	0.343	0	0.571	0	1.795	0	3.219	0
Pine potential	0.143	−4.7	0.299	−12.8	0.504	−11.7	1.673	−6.8	3.146	−2.3
Stanley Brook										
Prehistoric	0.021	−3.3	0.031	−21.9	0.039	−49.4	0.079	−69.0	0.293	−46.0
Current	0.022	0	0.039	0	0.077	0	0.255	0	0.542	0
Pine potential	0.019	−12.2	0.029	−25.9	0.038	−51.1	0.080	−68.8	0.308	−43.3
Tadmor										
Prehistoric	0.031	−38.6	0.098	−45.1	0.202	−48.5	0.632	−33.2	1.511	−14.7
Current	0.051	0	0.178	0	0.393	0	0.946	0	1.771	0
Pine potential	0.030	−40.8	0.095	−46.6	0.199	−49.4	0.615	−34.9	1.474	−16.8
Wangapeka										
Prehistoric	0.93	−9.7	2.82	−12.1	4.25	−9.8	9.49	−5.9	15.49	−1.8
Current	1.03	0	3.21	0	4.71	0	10.09	0	15.78	0
Pine potential	0.93	−9.7	3.02	−5.9	4.42	−6.2	9.63	−4.6	15.54	−1.5
Motupiko										
Prehistoric	0.034	−47.4	0.070	−66.3	0.130	−62.4	0.480	−44.2	1.266	−18.1
Current	0.064	0	0.208	0	0.346	0	0.861	0	1.545	0
Pine potential	0.037	−42.8	0.106	−49.2	0.170	−51.0	0.536	−37.7	1.272	−17.7

The percentages are relative changes to the current land use

The mean minimum annual 7-day low flow is widely used as an indicator in water resources management (Ministry of Environment 1998; Smakhtin 2001). The minimum annual 7-day low flows were lowest for the prehistoric condition, intermediate for the pine condition, and highest for the current land use (Fig. 6). The minimum 7-day low flow is lower for the alternative land cover scenarios because they have higher forest cover and increased ET. The predicted minimum 7-day low flows were on average about 20% and 15% lower at Woodstock under the prehistoric and maximum potential pine scenarios, respectively. These decreases in streamflow, particular, maximum potential pine scenario (15%) would accumulate on top of the maximum permissible decrease in river flow caused by groundwater extractions (a 12% reduction in streamflow at Woodstock) given in the Motueka Water Conservation Order (Environmental Court decision W7/2003), which does not take into account the flow impacts of land use/cover change.

This study demonstrated that the two alternative land use/cover scenarios had a greater effect on low flows than on annual flows over the entire Motueka Catchment (to Woodstock). This result agrees well with results reported by Gustard and Wesselink (1993), Tallaksen (1993) and Robinson (1991). The impacts of land use/cover change on low flows in some subcatchments were much larger. Consequently, while the overall effects of the alternative scenarios on water resources might be acceptable, the local effects in some tributary catchments might be unacceptable.

4 Conclusions

A prehistoric land cover scenario and a potential maximum plantation pine cover scenario were used to evaluate the impacts of land-cover change on water resources in the Motueka Catchment using a calibrated and validated version of the SWAT.

Total annual water yield decreased by 5.5% at Woodstock under the prehistoric land cover and 4.5% for the pine potential scenario compared to the current land use. However, the simulated decreases in total annual water yield in some tributary catchments was substantially larger; e.g. in Stanley Brook the decrease were 12.5% and 12.1% for the prehistoric and the pine potential, respectively. Substantial decreases in low flows were observed for the prehistoric and pine potential land cover scenarios. Streamflow decreased more than 10% for low flows that are exceeded 70–99% of time. In some tributary catchments low flows within the 50–99% exceedence level decreased by more than 40% for both land cover scenarios compared with the current land use. The predicted minimum

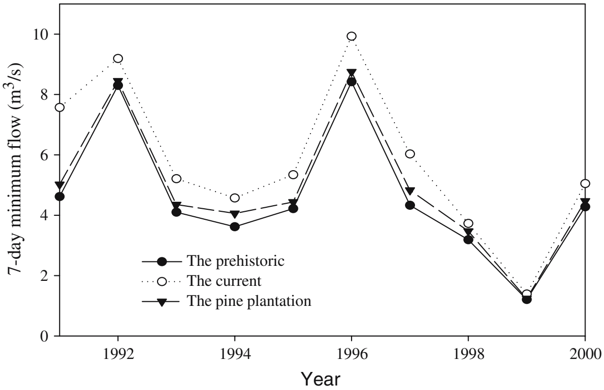


Fig. 6 Mean annual 7-day minimum flows at Woodstock

7-day low flows decreased by an average of about 20% and 15% at Woodstock, under prehistoric and maximum potential pine scenarios, respectively.

Generally, the effects of land use/cover change on the annual water balance were moderate in the larger catchment, but substantial in some tributary catchments where land cover changes were greatest and soil conditions did not favour soil moisture storage. The effect of the potential pine plantation land cover scenario on the annual water balance was generally less than the effect of the prehistoric scenario. However, this difference was not uniform throughout the catchment. Low flows were substantially lower under both alternative land use/cover scenarios. The percentage reduction on low flows was greater than the percentage reduction in total annual flows and was similar for both alternative scenarios.

The results from these simulations should help provide a context for discussion about policies for sustainable land and water management for the Motueka Catchment.

Acknowledgments The authors gratefully acknowledge the funding for this study from Landcare Research, New Zealand, and the Foundation for Research, Science and Technology (C09X0305). We would also like to thank two reviewers for their valuable comments on the manuscript.

References

Arnold JG, Allen PM (1996) Estimating hydrologic budgets for three Illinois watersheds. J Hydrol 176:55–77

Arnold JG, Srinivasan P, Muttiah RS et al (1998) Large area hydrologic modeling and assessment. Part I. Model development. J Am Water Resour As 34:73–89

Basher LR (2003) The Motueka and Riwaka catchment: a technical report summarizing the present state of knowledge of the catchment, management issues and research needs for integrated catchment management. Landcare Research, Lincoln, Canterbury, New Zealand

Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J Hydrol 55:3–23

Calder IR (1992) Hydrologic effects of land use change. In: Maidment DR (ed) Handbook of hydrology. McGraw-Hill, New York

Cao W, Bowden BW, Davie T et al (2006) Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability. Hydrol Proc 20:1057–1073

Chaplot V, Saleh A, Jaynes DB et al (2004) Predicting water, sediment and NO_3–N loads under scenarios of land-use and management practices in a flat watershed. Water Air Soil Poll 154:271–293

Duncan MJ (1995) Hydrological impacts of converting pasture and gorse to pine plantation, and forest harvesting, Nelson, New Zealand. J Hydrol (NZ) 34(1):15–41

Fahey B, Rowe L (1992) Land-use impacts. In: Mosley MP (ed) Waters of New Zealand. New Zealand Hydrological Society, Wellington North, New Zealand

Fenemor AD (1992) Water resource management in New Zealand. In: Mosley MP (ed) Waters of New Zealand. New Zealand Hydrological Society, Wellington North, New Zealand

Fohrer N, Haverkamp S, Eckhardt K et al (2001) Hydrologic response to land use changes on the catchment scale. Phys Chem Earth 26:577–582

Gustard A, Wesselink A (1993) Impact of land use change on water resources: Balquidder catchments. J Hydrol 145:389–401

Leathwick JR (2001) New Zealand's potential forest pattern as predicted from current species-environment relationships. New Zeal J Bot 39:447–464

Leathwick JR, Morgan F, Wilson G et al (2002) Land Environments of New Zealand: A Technical Guide. Ministry for the Environment, Wellington, New Zealand

Martin GN (1973) Characterization of simple exponential baseflow recessions. J Hydrol (NZ) 12(1):57–62

Ministry for Environment (1998) Flow guidelines for in-stream values. Wellington, New Zealand

Ministry for Environment (2000) New Zealand land cover database. Wellington, New Zealand

Moriasi DN, Arnold JG, VanLiew MW et al (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE 50:885–900

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models, part I a discussion of principles. J Hydrol 10:282–290

Robb C (1990) Groundwater model of Motueka/Riwaka Plains aquifer system. Lincoln Environmental Report 2325/1 for Tasman District Council, Richmond, New Zealand

Robinson M, Ganon B, Schuch M (1991) The comparison of hydrology of moorland of natural conditions, agricultural use and forestry. Hydrol Sci 36(6):565–577

Rowe L, Fahey B, Jackson R (1997) Effects of land use on floods and low flows. In: Mosley P, Pearson P (eds) Floods and droughts: the New Zealand experience. New Zealand Hydrological Society, Wellington North, New Zealand

Smakhtin VU (2001) Low flow hydrology: a review. J Hydrol 240:147–186

Srinivasan R, Ramanarayanan TS, Arnold JG et al (1998) Large area hydrologic modelling and assessment part II: Model application. J Am Water Resour As 34(1):91–101

Statistics New Zealand (2002) Monitoring progress towards a sustainable New Zealand. Statistics New Zealand, Wellington, New Zealand

Tallaksen LM (1993) Modelling land use change effects on low flows. In: Gustard A (ed) FRIEND. Vol I: hydrological studies. Institute of Hydrology, Wallingford, UK

TDC (Tasman District Council) (1995) Motueka/Riwaka Plains water management plan. Tasman District Council, Richmond

Walls GY (1985) Native bush remnants of the Moutere gravels, Nelson. Botany Division Vegetation Report 522, Botany Division, DSIR, Nelson