Ridgetops to the sea: developing sustainable management tools in New Zealand's Integrated Catchment Management project

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The Motueka Integrated Catchment Management (ICM) project is a nationally funded research programme developing tools to help make New Zealand's 'clean, green' image a reality, at large catchment scale. Internationally, it is recognised that effective catchment management requires integration of scientific disciplines to provide workable legislative structures and management tools for practical solutions (e.g. Schneiders and Verheyen 1998; Mance *et al*., 2002). The Motueka catchment near Nelson has been chosen as a case study for New Zealand because it is an area of rapid economic and population growth with corresponding environmental pressures. It has a relatively unspoiled environment with land uses ranging from pristine national park to planted pine forest and intensive horticulture, nationally recognised trout rivers, and economically important coastal fish and shellfish resources (including a growing aquaculture industry) off the rivermouth in Tasman Bay.

The Motueka ICM project is based around a 'ridgetops to the sea', collaborative learning approach to enhance sustainable management in the region. The project links hydrologists and other biophysical scientists with social scientists, economists, policy makers and communities in a holistic approach. It is one of the inaugural pilot basins in the UNESCO/WMO global HELP project (***H****ydrology for the* ***E****nvironment,* ***L****ife and* ***P****olicy*).

This paper details results from three of the varied research areas being integrated within the programme: social science (including ecological economics), hydrology and marine science. Many more researchers are developing sustainable management tools within a wider programme of research.

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BACKGROUND INFORMATION ON THE MOTUEKA CATCHMENT

The Motueka catchment (Figure 1) occupies 2170 km^2 in the north-west of the South Island. The Motueka River flows 110 km from an elevation of 1600 m to sea level where its mean flow of 82 m^3 s^{-1} delivers 65% of the fresh water to

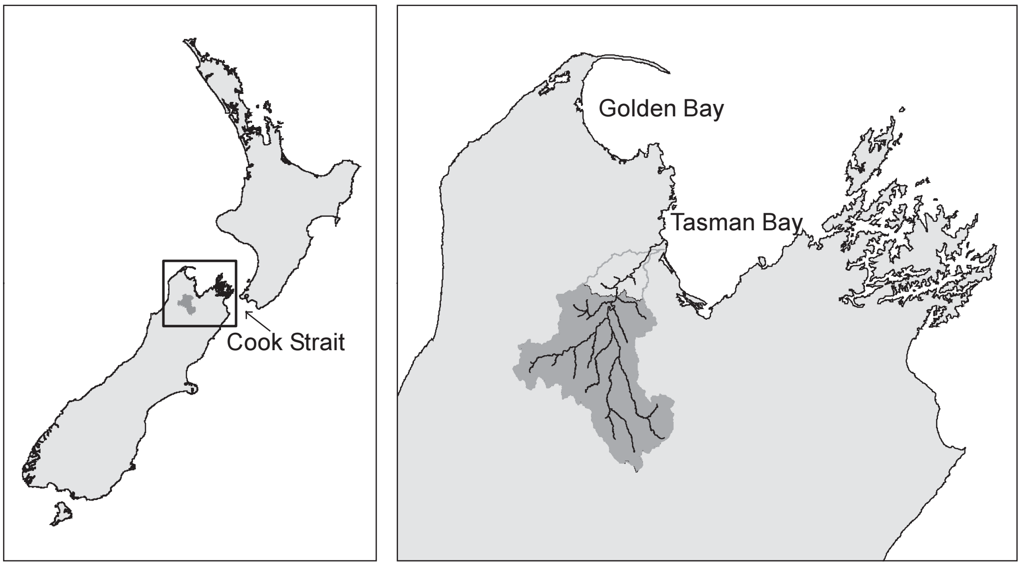

Fig. 1 Motueka River catchment, New Zealand. The dark shaded area represents the catchment above the Woodstock gauging station.

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Tasman Bay. Average annual precipitation ranges from 1000 to over 3500 mm in the western ranges. The climate is cool and humid with dry (austral) summers.

The Motueka catchment was originally covered in native podocarp and Southern Hemisphere beech (*Nothofagus*) forests. Since European settlement from the mid 19th century onwards, two-thirds of the catchment has been cleared, with roughly one-third now in exotic conifer forest and one-third in dryland pasture or crops. Horticulture (apples, kiwifruit, berryfruit, hops, and — historically — tobacco) is restricted to valley bottoms and the Motueka Plains, and is mostly irrigated, from rivers or groundwater.

The Motueka River supports an introduced brown trout fishery that attracts anglers from around the world. The rivers in the catchment are also used for canoeing, rafting, gold panning and other recreational pursuits. The upland marble terrain contains the deepest cave system in the Southern Hemisphere, which attracts international speleological exploration. Scallop and cockle harvesting are key activities in Tasman Bay and there is a rapidly expanding interest in mussel and other marine farming opportunities.

The catchment is sparsely populated (<1 per km^2) with a total population of 12 000, of which 7000 live in the town of Motueka. Population growth is among the highest in New Zealand at more than 2% per annum. Vineyards, marine farming, and tourism are adding to the diversity and productivity of the local economy.

SOCIAL SCIENCE — TWO WAY COMMUNITY INVOLVEMENT

Community Reference Group

A major focus of the Motueka ICM research programme is the involvement of stakeholders in the research, specifically the Tasman District Council as environmental management agency and the people living in the Motueka catchment. One way to facilitate this interaction has been through the establishment of a community reference group (CRG). This group comprises seven residents from throughout the catchment plus up to four researchers and policy makers. The CRG meets four to six times a year.

In a catchment where the research aim is more about protecting existing natural values than repairing damaged ones, one challenge has been to motivate sufficient interest to keep the CRG going. Surprisingly, the CRG has more than survived. While some initial participants have left, others have joined and a core group of seven people, of varied interests including farming, managing orchards, recreational fishing and tourism, take part in the meetings.

Several research initiatives have been developed from CRG meetings. Following a discussion about water quality results, landowners on the banks of the Sherry River became aware that their stock crossings were the likely cause of poor water quality in their river. This group of landowners, supported by staff of the council, the NZ Landcare Trust, and ICM researchers, investigated the problem and three of four stock crossings have now had bridges built by landowners.

One of the most significant outcomes has been the growing confidence and familiarity within the CRG, a key ingredient for learning and change. A second initiative, described below, has been group input into an influence matrix model for understanding the important factors that influence environmental outcomes at whole catchment scale. The trust built up among CRG members has allowed the free flow of discussion, including direct challenges to the assumptions, structure and usefulness of the model itself. This input, together with the group's observations about what factors most affect the future of the catchment, shows the value of working with 'non-researchers' when building models and reflects the degree of confidence, trust and capacity built over the last three years. The modelling takes an ecosystem services approach to the question of what constitutes catchment sustainability.

Ecosystem services

By way of background, ecosystem goods and services (Mooney and Ehrlich, 1997) play an important role in economic activity and in providing spiritual and recreational values (Daily, 1997). Fresh water is an ecosystem good, while the collection, storage, purification and transport of water are examples of ecosystem services. At a global scale, scientists generally agree humans depend upon 17 key ecosystem services. These include: processes that maintain atmospheric gas composition; climate parameters; disturbance regimes; water quality and supply; erosion control; soil formation; nutrient cycling; the treatment of wastes; pollination; biological control; the provision of habitat; food production; the supply of raw materials; genetic resources; recreation and culture services (Costanza *et al.*, 1997).

Human economic activity depends on the provision of ecosystem goods and services (Binning *et al.*, 2001). Patterson and Cole (1999) estimated that the New Zealand economy annually draws on flows of ecosystem goods and services to the economic value of approximately one half of our annual GDP. Therefore, the problem of sustaining current levels of economic production and consumption at national, regional and catchment scales also implies a need to sustain ecosystem services (Cole and Patterson, 1998).

The scientific methods chosen to determine values relating to the provision and maintenance of ecosystem services must be chosen with reference to an understanding of future community goals (Costanza and Folke, 1997). For example, if a local community agreed on *only* one goal — to maximise economic returns — then no effort would be needed to sustain ecological or social systems until they impinged upon that economic goal. In theory, market prices would play an important role in regulating economic activities so that they did not exceed local ecological and social limits. The main problem with this approach is that economic efficiency is not society's only goal; other goals like social fairness and sustainability are both feasible and desirable.

We first asked the Motueka CRG what their future goals were for the management of the Motueka Catchment. This exercise confirmed that members were concerned with more than just economic development. Their general management goals included social wellbeing, economic and ecological resilience, social equity, sustainable management and development. This is an important insight because we cannot explore the problem of sustaining ecosystem services in isolation from other community goals.

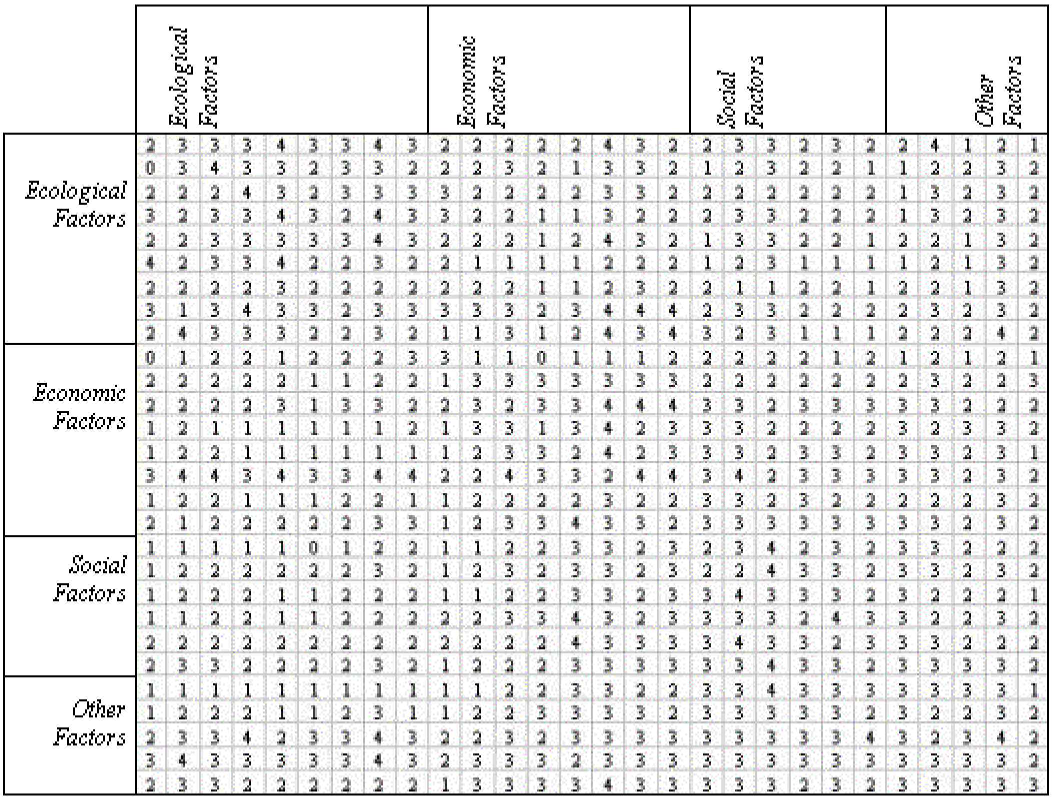
We next asked the CRG what factors they considered affected the achievement of these goals. From an initial 178 factors, 28 key factors were identified. To address the problem of how to study ecosystem services in connection with other economic and social goals/factors we trialled a whole-system participatory modelling methodology based on earlier research by Vestor (1976) in urban systems. The influence matrix provides an opportunity for community members to express a type of whole-system preference using a subjective assessment of perceived influence between system factors. The use of influence as a unit of measurement over the entire catchment helps to overcome the commensuration problems typically associated with whole-system analysis in conventional economics (Costanza and Hannon, 1989;Patterson, 1998).

Influence matrix results

A catchment influence matrix (Table 1) is data rich and possible to analyse in different ways. We used the data to:

1. Rank individual and groups of factors to identify the strongest influence on progress towards community goals.

Table 1. Influence matrix completed by the Motueka community reference group. The location of individual row and column factors is indicated according to factor groupings only. When drawn in detail, each individual factor shares the same row and column number. An individual score represents the estimated influence of a given row factor on a particular column factor as measured subjectively on a scale of 0 to 5 (0 representing no influence, 3 an intermediate influence and 5 a strong influence).



	Ecological Factors									*Economic Factors*								*Social Factors*						*Other Factors*				
Ecological Factors	2	3	3	3	4	3	3	4	3	2	2	2	2	2	4	3	2	2	3	3	2	3	2	2	4	1	2	1
	0	3	4	3	3	2	3	3	2	2	2	3	2	1	3	3	2	1	2	3	2	2	1	1	2	2	3	2
	2	2	2	4	3	2	3	3	3	3	2	2	2	2	3	3	2	2	2	2	2	2	2	1	3	2	3	2
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	2	4	3	3	3	2	2	3	2	1	1	3	1	2	4	3	4	3	2	3	1	1	1	2	2	2	4	2
Economic Factors	0	1	2	2	1	2	2	2	3	3	1	1	0	1	1	1	2	2	2	2	2	1	2	1	2	1	2	1
	2	2	2	2	2	1	1	2	2	1	3	3	3	3	3	3	3	2	2	2	2	2	2	2	3	2	2	3
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	2	1	2	2	2	2	2	3	3	1	2	3	3	4	3	3	2	3	3	3	3	3	3	3	3	2	3	2
Social Factors	1	1	1	1	1	0	1	2	2	1	1	2	2	3	3	2	3	2	3	4	2	3	2	3	3	2	2	2
	1	2	2	2	2	2	2	3	2	1	2	3	2	3	3	2	3	2	2	4	3	3	2	3	3	2	3	2
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	2	3	3	2	2	2	2	3	2	1	2	2	2	3	3	3	3	3	3	4	3	3	2	3	3	3	3	2
Other Factors	1	1	1	1	1	1	1	1	1	1	1	2	2	3	3	2	2	3	3	4	3	3	3	3	3	3	3	1
	1	2	2	2	1	1	2	3	1	1	2	2	3	3	3	3	2	3	3	3	3	3	2	3	2	2	3	2
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	3	4	3	3	3	3	3	4	3	2	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	2
	2	3	3	2	2	2	2	2	2	1	3	3	3	3	4	3	3	3	3	3	2	3	2	3	3	3	3	3

2. Better understand the relative importance and functional role of individual factors.
3. Help prioritise research effort towards those system factors or factor groups that play a leading role in progress towards future community goals.

Ranking of the 28 factors of the influence matrix (Table 1) indicated that the five most influential factors (in rank order) were: primary industries, policy, plans, rules and legislation; governance of social institutions; economic inputs; and water quality and supply. It is not surprising that primary industries and economic inputs feature as highly influential factors because the local economy is strongest in the primary (agricultural/horticultural) and tertiary (service) sectors. Water quality and supply is also recognised as an influential factor because its limitation has the ability to constrain economic activity on a large scale. However, it is interesting that social factors (policy, plans, rules and legislation and governance of social institutions) were ranked so highly.

Ranking of the six main groups of factors based on their relative system-wide influences also yielded interesting results. Governance of social institutions and policy, plans, rules and legislation yielded the highest weighted group scores of 19, followed by non-local influence and ecological group factors at 17, social group factors at 15, and economic group factors at 14. It is again evident that economic factors do not hold a monopoly on system-wide influence. Surprisingly, three different groups of social factors have the greatest system-wide influence (accounting for 54% of the total group influence) followed closely by ecological factors. These results are highly significant from a policy perspective. Management of the catchment towards multiple community goals needs to take social and ecological factors into consideration, especially the role of social institutions.

In summary, the existence of multiple community goals implies that we cannot focus on the study of important themes, like sustaining ecosystem service capacity, in isolation from social and economic factors. Participatory modelling methodologies like the influence matrix provide an opportunity for researchers to measure how community members express their preferences at a whole-system level of catchment scale. The development, testing and use of participatory methods of this kind in an integrative research context will play an important future role in helping us manage catchments towards economic, social and ecological community goals. While further refinements are needed in this modelling methodology, it has already played an important role in helping us shape our research priorities in a whole-system context.

HYDROLOGY – LAND USE IMPACTS ON RIVER FLOWS

New Zealand has a diverse and temporally dynamic land usage. The main drivers of land use change are newly evolving economic opportunities in agriculture, horticulture and forestry. In this research strand, we demonstrate the difficulties experienced in assessing the impacts of land use change when modelled at the large scale.

Two separate models have been used in the project to investigate the impacts of land use change at large catchment scale. The models are SWAT (Soil and Water Assessment Tool; Arnold *et al*., 1998) and a new derivation of the DHVSM (Distributed Hydrology-Vegetation-Soil Model) of Wigmosta *et al*. (1994). Both models have a distributed spatial arrangement and can claim some form of physical basis (i.e. based on physical equations with measurable input parameters).

DHVSM

The DHVSM works on a square grid cell arrangement and concentrates on solving the water balance for each grid cell. The processes simulated at each grid cell are precipitation (including throughfall and interception from a canopy); evapotranspiration (using a simplified Penman-Monteith equation); infiltration into the soil and groundwater; subsurface flow and overland flow. The grid cells used in this simulation are 30 × 30 m, from a digital elevation model of the catchment. Once overland or subsurface flow reaches a channel, the water is routed down the channel using a simple time-lag function based on the known recession curve for the Motueka at Woodstock gauging station.

SWAT

SWAT is a complex model with many different combinations of process representations possible. A full description of the different options used in this study is in Cao *et al*. (in prep). The major difference between DHVSM and SWAT is the spatial representation; SWAT uses a combination of sub-basins and hydrological response units (HRU). HRU are portions of a sub-basin that possess unique land use/management/soil attributes. The inclusion of HRU allows SWAT to account for heterogeneity of the land use/management and soil properties within a sub-basin. HRU form the basic computational unit for estimating the water balance; they differ from DHVSM grid squares in that they vary in size according to the heterogeneity of soils and vegetation cover within a sub-basin.

Input data

The Motueka catchment is extremely diverse in terms of rainfall, geology and land use, which presents interesting problems for deriving input data to run distributed hydrological models. Soils and land cover data were derived from national databases; for soils this includes water-balance type properties distributed via soil type (based on previous soil surveys and association with underlying geology). In the agriculturally productive areas of the catchment the soils coverage is reasonable, but in the mountainous regions the coverage is poor. For land cover, the data are derived from satellite overpasses in the mid-1990s, which have been converted into the Land Cover Data Base.

The annual precipitation in the Motueka catchment ranges from more than 3500 mm in the western side of the catchment to around 950 mm in the lower, eastern side. Rainfall has high variability due to a complex, rugged terrain with the arrangement of the mountains and the predominately westerly airflows resulting in a strong precipitation gradient from west to east. There is an irregular spacing of precipitation gauges around the catchment with 18 gauges with long enough records for use in a long-term modelling study. Unfortunately these are distributed mainly in the lower parts of the catchment. An algorithm was developed for both models that calculated daily rainfall at a point based on an interpolation from annual rainfall. The annual rainfall map has been drawn by the Tasman District Council (the environmental regulators for the catchment) based on as much local rainfall information as possible and expert knowledge of the area.

Results

Following calibration and validation of the models, three land cover scenarios were run for the period 1990–99 (from when a good rainfall and river flow coverage could be obtained). The first scenario simulates the current land use; the second represents a 'restoration' of the catchment to its pre-European state with a predominance of *Nothofagus* cover. This represents an 'increase' in indigenous forest cover from the current 37% to 88% (the remainder is either too high for trees to grow or wetland). The third scenario assumed that exotic plantations (*Pinus radiata*) cover as much as possible of the catchment without replacing indigenous vegetation and wetland. This is based on sensible elevation limits for economic viability of plantation forestry in the region. In this scenario the exotic plantations go from the current 27% to around 50% of the catchment.

Some keys results are highlighted in Table 2. The most striking aspect is the large difference between the two models. In the case of average annual discharge the DHVSM shows an increase in flow with the increase in taller vegetation while SWAT shows the opposite. Both of these results differ considerably from small catchment studies in the region, which have shown decreases in annual flow of up to 50% following afforestation in the dry eastern part of the catchment (Duncan, 1995).

Table 2. Average annual discharges from observations and simulated scenarios, 1990–1999 ($m^3 s^{-1}$) for the Motueka at Woodstock. Simulated scenarios are shown for two models: DHVSM and SWAT, both described in the text. DVHSM has been revised in light of expert knowledge to give the second column, DVHSM2.

Hydrograph	*SWAT*	*DVHSM1*	*DVHSM2*
Observed	58.7	58.7	58.7
Current scenario	54.7	60.0	57.3
Prehistoric scenario	-5%	+9%	-11%
Maximum pine scenario	-4.5%	+3%	-3.%

The most remarkable result is the difference in low flows following 'restoration' of the prehistoric vegetation cover: DHVSM suggests a 22% increase in flows while SWAT suggests a 20% decrease. For the maximum pine scenario DVHSM simulates a 2% decrease in annual minimum seven-day low flows while SWAT simulates a 15% decrease in the same low flow measure. A possible reason for DHVSM showing an increase in low flows with the prehistoric vegetation cover can be traced to the simplification of the Penman-Monteith equation for evapotranspiration. Indigenous New Zealand vegetation often has high canopy resistance to evaporation (e.g. Köstner *et al.*, 1992) and the values used in DHVSM reflect this. Consequently during the summer months the transpiration values from the indigenous forest cover are low and more water is available for streamflow. This effect is compounded by the simulated soil water storage remaining high during the summer so that transpiration occurs at maximum rates. In SWAT the canopy interception dominates the evapotranspiration term and even during summer months there is less water available for streamflow.

In light of expert knowledge, the version of DHVSM was modified to give a fuller version of the Penman-Monteith equation for evapotranspiration. This lessened the importance of transpiration, relative to canopy interception loss. The results can be seen in Table 2 (fourth column – DHVSM2). In terms of low flows, the modified DHVSM showed a 28% decrease in annual minimum seven-day low flows, and a 9% decrease for the maximum pines scenario. Both these scenarios are closer, although not identical, to the SWAT predictions and match expectations from empirical studies. In this case expert judgement has been used in identifying model deficiencies and an iterative model development has provided comparable answers for resource managers assessing the results from both models. In this case it is critical assessment of results from science end-users, rather than local community end-users, that has assisted model development.

Discussion

Work with the community reference group, using an influence matrix, has identified that economic factors are not the only influence on community goals for the Motueka catchment. It is possible that economic factors that drive land use change may be overruled by ecological or social factors defined by a study on the impacts of land use change. In attempting to do this, using two different hydrological models to simulate the impacts of land use change, quite different results have been obtained. The SWAT simulation is closer to what might be expected but the initial results from DHVSM pose problems for land managers considering hydrological impacts of land use change. A revised model, in light of expert knowledge has produced results comparable to SWAT which gives greater confidence for a land manager making decisions concerning long-term sustainability of water resources and land management in the Motueka catchment.

MARINE SCIENCE –MOTUEKA RIVER'S IMPORTANCE TO PRODUCTIVITY IN TASMAN BAY

Land use change in the catchment does not affect only river flows. The Motueka catchment discharges into the western side of Tasman Bay (Figure 1). Land uses and catchment development have potentially significant effects in this bay. Here an extensive intertidal (756 ha) and shallow subtidal delta provides a transition zone to the marine environment of the bay. Long-term (seasonal and inter-annual) assessment of the distributions of temperature, salinity, inorganic nutrients, water clarity and phytoplankton and benthic microalgal biomass indicate that the freshwater plume from the Motueka River affects an area extending >10 km into Tasman Bay (Gillespie, 2003; MacKenzie and Gillespie, 2003; MacKenzie *et al*., 2003). Although preliminary circulation modelling of Tasman Bay (Tuckey *et al*., 2003) and assessment of freshwater nutrient discharge rates indicate that inorganic nutrients are contributed mainly by the inflow of offshore oceanic waters from Cook Strait, riverine sources periodically result in strong concentration gradients that stimulate photosynthetic production within the plume. This linkage between the land and sea, via the Motueka River, is an important part of Integrated Catchment Management research. In particular, a combined model is being developed to link nutrient and contaminant loss from the catchment to Tasman Bay circulation models.

Effects on salinity, phytoplankton and benthic productivity

River inflows can have a profound effect on the density structure of the western side of the bay (particularly after heavy rainfall, e.g. Figure 2) by creating a less dense surface layer that inhibits vertical mixing of the water column. Within the plume-affected region, three aquaculture management areas totalling ~4200 ha have been zoned for development of longline mussel culture (Figure 2) and the remaining offshore regions are used for commercial scallop enhancement and harvest. The observed plume-affected phytoplankton (chlorophyll α) profiles indicate that, although sufficient particulate food is available to support a longline mussel culture industry, consideration of the stratified conditions and predominantly subsurface chlorophyll *a* maxima (e.g. Figure 3) will be required to optimise farm management.

Observed N:P:Si ratios in the bay suggest that nitrogen is the most limiting to phytoplankton productivity. The loss of nutrient forms of nitrogen through microbial denitrification (conversion to N_2 gas) in the bottom sediments (Christensen *et al.*, 2003) appears to be more than sufficient to compensate for the total dissolved inorganic nitrogen discharge into the bay through freshwater sources. Thus, under the present land usage regime, nutrients delivered from the Motueka catchment can be considered a positive influence on primary production with little potential to create the over-enriched conditions common to many coastal regions in other parts of the world (Cloern, 2001, Conley *et al*., 2002).

Benthic shellfish (scallops, oysters, etc.) are less dependent on phytoplankton as a food source because their feeding environment is augmented to a larger extent by resuspension of benthic microalgae from the seabed (Gillespie, 1997, 2003). Benthic shellfish, however, can also be adversely affected by high concentrations of inorganic sediments. A fluctuating near-bottom high turbidity layer has been observed within the plume region with highest values corresponding to periods of maximum tidal flow. Inorganic suspended solids concentrations >20 g m^3 within this layer (<50 mm above the seabed) appeared to strongly inhibit scallop feeding. Although it is likely that variations in river sediment discharges (Basher and Hicks, 2003) affect the intensity and composition of the high turbidity layer, these relationships have not yet been fully evaluated. Preliminary observations suggest that major flood events are an important contributor to sediment concentrations within the feeding environment of benthic shellfish and that conditions inhibitory to scallop feeding can persist for a period of months after a flood due to subsequent tidal resuspension. There is a strong possibility that dredging and trawling disturbances may also contribute to the persistence of high suspended solids concentrations of near-bottom waters.

At present there is a good scientific understanding of the possible effects of land-derived nutrients on potential aquaculture sites but no empirical or modelled data to assess how much nutrient and contaminants are reaching potential

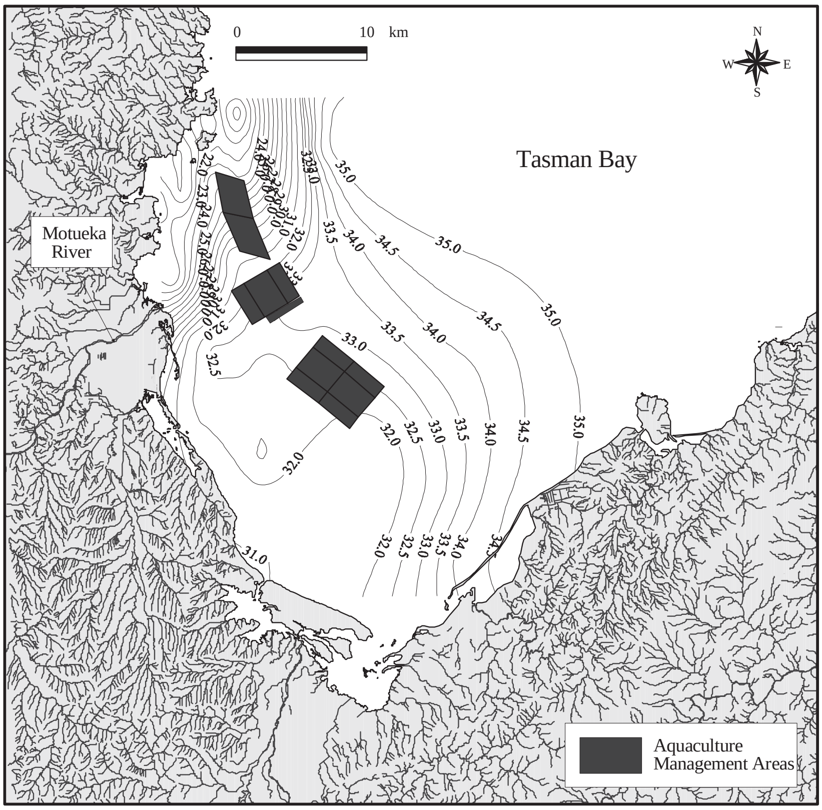

Fig. 2 Example of surface water salinity plume off the Motueka River mouth. Data collected 3 days after a rainfall event (river inflow 409 m^3 s^{-1})

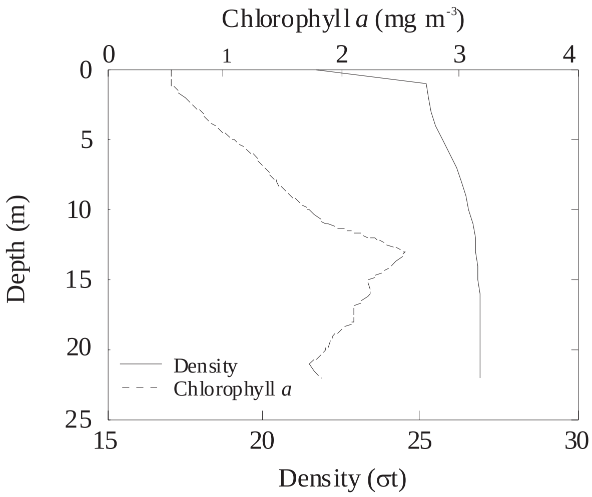

Fig. 3 Example of seawater density and chlorophyll a *profiles at a site in Tasman Bay 9 km offshore from the Motueka River mouth. Data collected 5 days after a rainfall event (river inflow 409 m^3 s^{-1}).*

aquaculture areas. A major stream of work over the next two years is to link a surface hydrology model (SWAT) with the Tasman Bay circulation model to assess the amount of nutrients and contaminants entering the bay during flood events and how the nutrients move within the bay. This will provide a valuable tool for legislators and marine farming planners to assess impacts of land use change and the optimal positioning of marine farms to either avoid or be within the Motueka freshwater plume.

DISCUSSION AND CONCLUSION

The integrated management of a complex river catchment such as the Motueka requires consideration of social, economic and biophysical factors. The relatively pristine nature of the current environment is highlighted by the consideration of river-borne nutrients as a positive aspect for the marine environment, rather than a problem through increasing eutrophication. The challenge is to maintain this high environmental standard while allowing development with consequent land-use change and taking into account community aspirations for their environment. Tourism (both marine and land based) is a major industry in this region and any decline in water quality and quantity is likely to impact this. In-stream water quantity is being preserved through a negotiated Water Conservation Order, which sets a limit of 12% of the flow extracted in the Motueka mainstem, and 6% in the Wangapeka River, as measured by the actual residual flow. Water quality issues have focused around bacteria, particularly during summer storms (e.g. 20–21 February, 2004) when agricultural and stormwater contaminants are flushed towards popular recreational areas. There has been a major concern of cows having access to water bodies, leading to faecal contamination, and this is being addressed through cow-crossing bridges and riparian fencing.

Current tools used for management, such as the hydrological models described in this paper, do not provide enough information by themselves to allow integrated catchment management. Although simulating spatially integrated hydrological processes, at present they do not link with the marine environment (necessary for knowledge of sediment and nutrient fluxes) and have no consideration of social and environmental factors. In addition to this, the two hydrological models at first gave contradictory information when simulating the impact of land use change on river flows. This was amended in the light of expert knowledge. A major focus of future research in the programme is to develop tools that do truly integrate biophysical, economic and social factors so that future management scenarios can be simulated and cumulative impacts assessed. The first step in this direction is the linking of SWAT with the Tasman Bay circulation modelling and to downscale ecosystem service modelling from the regional economic scale to within-catchment scale. The integration of social factors is planned through an increased participatory framework in setting the research questions to be asked and designing new models to answer them.

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