Monitoring land use change in the Lake Taupo catchment between 1975, 1990 and 2002 using satellite remote sensing data

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Abstract

Conversion of native vegetation into farmed grassland in the Lake Taupo catchment commenced in the late 1950s. The lake's iconic value is being threatened by the slow decline in lake water quality that has become apparent since the 1970s. This decline is due to increased nitrogen (N) leaching from the catchment, with 95% of the 'manageable' leached N estimated to be sourced from livestock farms. We report the usefulness of land use change data derived from historic satellite scenes (1975, 1990 and 2002), as a means of identifying critical areas within this large catchment that might warrant targeting for management change to help reverse the declining water quality. There were no large amounts of farmland or exotic forestry developed from indigenous vegetation after 1975. However, reducing the area of bare soil in grassland and exotic forest land use classes is suggested as one approach that may help reduce N leaching to ground water and the lake.

Keywords: satellite remote sensing, nitrate leaching, land use change, livestock farming, land management

Introduction

Lake Taupo is a major tourist attraction located in the central North Island, New Zealand, which is famous for its large size and exceptionally high water quality. Grassland farming commenced in this catchment in the 1950s and since the 1970s nitrate concentrations in streams from agricultural sub-catchments have risen significantly, as they have in the deep waters of the lake. Phytoplankton growth has also risen as a consequence of this increased supply of nitrogen (N) to the lake (Vant & Huser 2000; Hadfield *et al.* 2001; Vant & Smith 2004; Gibbs 2005). Specific N loads in streams from indigenous vegetation and forestry catchments are in the order of 1 - 2.5 kg N/ha and have changed little over time. In comparison, N loads from agricultural sub-catchments are in the range 7 - 9 kg N/ha. Stream water N concentrations are predicted to increase in the future as ground waters, which are already contaminated, flow into streams or directly to the lake (Hadfield *et al*. 2001; Vant & Smith 2004). Since no useful stock census data are available for the early years of agricultural development in the catchment, other indicators like the change of land use (e.g. increase of land in pasture) are needed to support the hypothesis that livestock farming is the major contributor to increased concentrations of groundwater N.

Retrospective analyses using satellite remote sensing information dating back to 1975, may give understanding of land use change processes active in the region during that period. Satellite data are a valuable source for recent and historic information on land use and can be used to document change over time. The first satellite series LANDSAT-MSS had a low geometric (60 m) and spectral resolution (four spectral bands: visible green and red bands, and two near infrared bands). In 1983 LANDSAT-TM was launched with 30 m ground resolution and six spectral bands in the visible and near infrared spectral zones and one band in the thermal infrared part of the spectrum. The main advantage of the LANDSAT programme is its data archive, which allows retrieval of data acquisitions back into the early 1970s. Satellite scenes need to be pre-processed by performing geometric (adjusting the images to a map-system), atmospheric and topographic corrections in order to compare the data from different acquisition times and illumination situations. Data are then classified to differentiate the object classes: indigenous forest, farmed grassland, exotic forests, native grass/scrub vegetation, bedrock/juvenile soil, urban areas, wetlands and water. Land use data derived from satellite remote sensing, combined with ancillary data from the Land Environment of New Zealand (Leathwick *et al*. 2002) (e.g. drainage, parent material) and New Zealand Land Resource Inventory databases (e.g. slope and soil maps) can be used to identify critical areas where site specific management may contribute to the overall aim of a 20% reduction in total 'manageable' N entering the lake (Environment Waikato 2007). The sub-hectare resolution of these images may also allow within-farm analyses to be performed.

As soils of the catchment area are highly erodible, the change of land use, e.g. from indigenous to exotic forests or to pasture, can increase the soil erosion and N leaching potential (Dyck *et al*. 1985). To assist in the development of a sustainable management system to improve water quality of the catchment, an understanding of past and present land use, and the location of intensive land use

Table 1 Satellite data selected for this study. Path/Row is a descriptor used to define the target image. Spectral bands used are in the visible blue (b), green (g) and red (r), and the near- (nIR) and thermal-infrared (mIR) bands of the light spectrum.

Sensor	Acquisition date	Path /Row	Ground resolution [m]	Spectral resolution
Landsat-2 MSS	22 Dec. 1975	76 / 87	60	4 bands (g, r, nIR, nIR)
Landsat-2 MSS	15 Feb. 1976	76 / 87	60	4 bands (g, r, nIR, nIR, mIR)
Landsat-5 TM	25 Dec. 1990	72 / 87	30	6 bands (b, g, r, nIR, nIR, mIR)
Landsat-7 ETM	22 Oct. 2002	72 / 87	30	6 bands (b, g, r, nIR, nIR, mIR)

within the catchment, would be useful. However, detailed historic land use information, and historic, useful, animal census data are not available to describe land use change or intensification of use. This paper examines the value of satellite remote sensing data to generate changing land use and land management information at a catchment scale, using the Lake Taupo catchment as an example.

Material and Methods

Remote sensing data

For the analysis of land use in the Lake Taupo catchment, four satellite scenes were used from the years 1975 and 1976, 1990 and 2002 respectively (Table 1). The first satellite series LANDSAT-MSS had a low geometric (60 m) and spectral resolution (four spectral bands: visible green and red bands, and two near infrared bands). LANDSAT-TM was launched in 1983 and had a 30 m ground resolution and six spectral bands in the visible and near infrared spectral zones and one band in the thermal infrared part of the spectrum.

As the catchment area could not be covered completely with a single satellite image in 1975, an additional scene from 1976, which was partly cloudy, was added. Since image acquisitions were only 2 months apart, these data were used for the land use classification and are hereafter referred to as 1975. The later scenes covered the entire area of the Lake Taupo catchment (Fig. 1).

All satellite image data were geo-referenced to the New Zealand Map Series 260 topographic maps (scale 1:50,000) of New Zealand. Due to the different acquisition dates the images were influenced by varying illumination effects, and different atmospheric situations. Also, as topography influences spectral reflectance of target objects, correction chains for the atmospheric and topographic distortion were applied to all satellite images (Fig. 2). Further details of the correction algorithms can be found in Brauer (2003).

Land use classification (Fig. 3)

Computer-aided classification procedures pursue the goal of clustering the image pixels based on spectral signatures to create generalised thematic maps (Lillesand & Kiefer 1994). The main assumption of a classification scheme is the potential to cluster similar or homogeneous spectral characteristics of certain objects into groups. Using mathematical algorithms the computer tries to find characteristic signal properties of an object to differentiate it from other objects.

Land use classification was an iterative, stepwise process. First, the data were statistically conditioned. By applying a Principle Component Analysis, the spectral information of several multi-spectral bands was condensed into a smaller set of statistically independent bands which became the input for all of the following processing steps.

A hybrid classification approach, as described by

Figure 1 Frames of satellite imagery used for extraction of data from the Lake Taupo catchment.

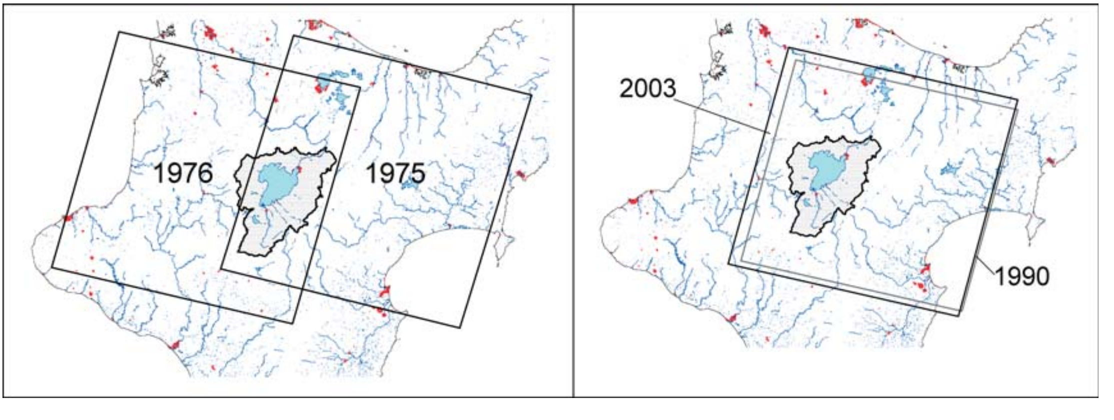


Figure 2 Pre-processing chain of satellite data (Brauer 2003).

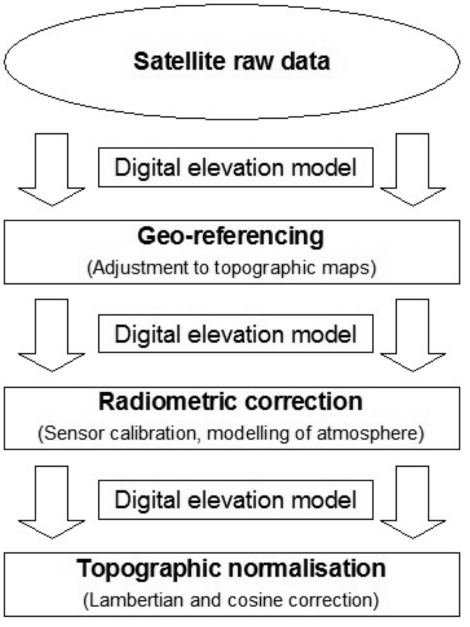


Figure 3 Land use classification chain.

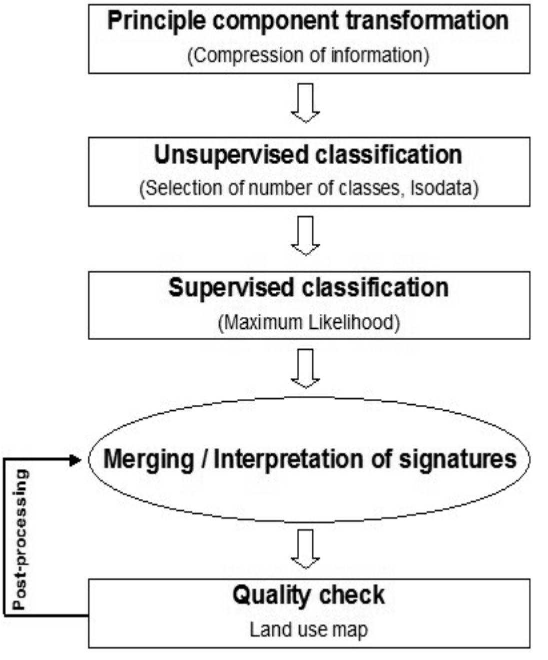


Table 2 Description of the different land use classes.

Class name	Description
Indigenous forest	Characterised by native woodland vegetation.
Exotic forests	All areas in which forestry is grown for timber. Monoculture plantations and the practice of harvesting by clear-cut allows the spectral separation from the class 'Indigenous forest'.
Farmed grassland	All pasture used for sheep, cattle and deer grazing. At regular intervals ploughing is used for pasture renovation, usually including a crop, so bare soil can also seen in this class.
Water	All lakes and large rivers within the catchment area.
Native grass/Scrub vegetation	Scrub and tussock vegetation. The spectral response of these vegetation types is very similar, due to the dominating woody components and low chlorophyll content of grasses.
Urban area	Urban area is a spectral mixture of houses and vegetation of gardens and trees. With knowledge from the land resource inventory urban areas could be classified.
Bedrock/Juvenile soils	All the volcanic and lava surfaces southwest of Lake Taupo.
Wetland	All vegetated areas around lake shores and rivers characterised by their specific spectral signature. Wetlands possess great ecological importance for improvement of quality of adjacent waters.

Hostert and Huth (1995), was used to retrieve land use information from the satellite imagery. This approach required no *a priori* information to build classes as statistical clustering algorithms generated the classes automatically. The allocation to a specific land use was done using information from the New Zealand Land Resource Inventory (NZLRI) (Leathwick *et al.* 2002).

The resulting thematic land use images were checked for errors and the training classes were adjusted to minimise classification errors.

Results

In the land use classification, eight different classes were selected, similar to those used in the NZLRI (Leathwick *et al.* 2002) (Table 2). In this work we have focussed on the major land use classes: Indigenous forest; Exotic forests; and Farmed grassland; since these represent most of the land in the catchment. These class distributions, as areas and as percentages of the Lake Taupo catchment land area, are shown in Table 2.

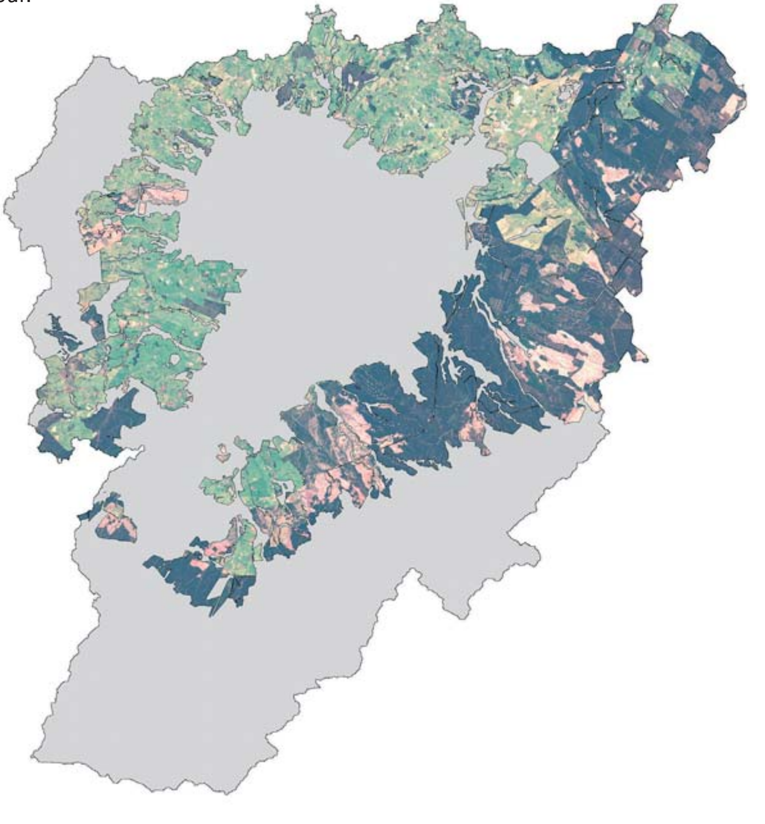
Since the spectral signature of bare soil in grassland

Table 3 Distribution of land use classes and bare soil for the classes 'Farmed grassland' and 'Exotic forest' in the Lake Taupo catchment in 1975, 1990 and 2002.

Class name	1975 Total area (ha)	1975 (%)[1,2]	1990 Total area (ha)	1990 (%)	2002 Total area (ha)	2002 (%)
Land use classes						
Indigenous forest	87 321	26.1	83 540	24.9	82 994	24.8
Farmed grassland	75 060	22.4	80 799	24.1	76 825	22.9
Exotic forests	89 214	26.6	93 314	27.9	97 282	29.0
Sum	251 595	75.1	257 653	76.9	257 101	76.7
Bare soil in land use classes						
Farmed grassland	7082	9	18132	22	3500	5
Exotic forests	23115	26	15577	17	15928	16
Sum	30197	18	33709	19	19428	11

[1] Land use classes: percentage of the total catchment area (334 930 ha), lake excluded.
[2] Bare soil: percentage of the land use class.

Figure 4 True colour satellite imagery from 22 October 2002. All land use classes and the lakes are masked except Farmed grassland and Exotic forest. Bare land in these classes appears as a white-pinkish colour.



and in exotic forest appears similar in the satellite imagery, visual interpretation of the imagery was necessary. Bare soil was assigned to their specific land use classes based on their location and the surrounding major land use. Figure 4 is the satellite image from 2002, showing bare ground in the farmed grassland and exotic forest classes.

Table 3 shows the area and percentage of the total 'land' catchment occupied by these classes for the specified years, and the areas of bare ground within Farmed grassland and Exotic forest classes. Areas within the satellite imagery that appear as bare soil reflect management practice at that time.

In order to balance land use change, the 1975 land use

Table 4 Change in land use between Indigenous forest, Farmed grassland and Exotic forest, from 1975 to 1990 and 1975 to 2002, expressed as a percentage of the land area in each class in 1975 (100%).

1975 (= 100 %)	1990		2002	
	Farmed grassland	Exotic forest	Farmed grassland	Exotic forest
Farmed grassland	95.3[1]	3.6[1]	86.9	8.0
Exotic forest	4.2	94.8	4.5	94.5
Indigenous forest	3.9	1.6	3.9	2.1

[1] Of the Farmed grassland in 1975, 95.3% remained as Farmed grassland and 3.6% had been converted to Exotic forestry by 1990.

situation was set as the base level (100%), to allow change between the classes to be computed (Table 4). This shows that, of the land in Farmed grassland in 1975, only 87% remained in Farmed grassland 27 years later with the difference mostly accounted for by the increased area in Exotic forestry. Over the same period, the reduction in area of Exotic forestry was less than for Farmed grassland, with 4.5% of Exotic forests converted to Farmed grassland. Almost all of the loss of Indigenous forest to either Farmed grassland or Exotic forest had taken place by 1990.

Discussion

Land use classification using historic satellite imagery of the Lake Taupo catchment has shown land use changes over time. Considering the absolute change between 1975 and 2002, a decrease of 4327 ha of Indigenous forest was detected, while Farmed grassland increased by 1765 ha and Exotic forests by 8067 ha. The increased area in exotic forests resulted from the loss of Indigenous forest and native grassland, and since 1990, loss of grassland. During this period 5506 ha of native grass/scrubland was converted mainly to plantation forestry (results not shown). Other changes in land use were relatively small. Classification errors, especially in the change between 60 to 30 m pixel resolution, will also be presented as 'apparent change' in land use.

All of the indigenous forest loss occurred between 1975 and 1990, during which time there was an increase in Farmed grassland (5739 ha) and Exotic forests (4100 ha). In contrast, during the period 1990-2002 there was little change in the area of indigenous forest (-546 ha); a reduction in the area of Farmed grassland (-3974 ha); and a continued rise in the area in Exotic forest (+3968 ha). On a catchment scale, these changes over 27 years were small, with declines of 1.3% in Indigenous forest and increases of 0.6% in Farmed grassland and 2.4% in Exotic forest. While the area of Farmed grassland increased during the first 15 years and then subsequently declined, there would most likely have been an ever-increasing stocking rate and use of fertiliser N that would have negatively affected water quality (Vant & Huser 2000). Such changes in 'intensity' of land use, as it affects the environment, cannot be accounted for when only considering changes in the area of each land use class and the change in percentage of bare soil within classes.

Besides the absolute change in area of managed land, management practice has a strong impact on nutrient and sediment movement. At each of the image acquisition dates, significant parts of the area were in bare soil due to ploughing or the practice of clear-cut harvesting of Exotic forests. Newly sown pastures or Exotic forests planted in the previous 2 or 3 years may have been erroneously classified as bare soil. Even so, using data in Table 3, the combined amount of bare soil in Exotic forest and Farmed grassland classes was large, being 9% of the catchment's total land area in 1975, 10% in 1990 and 6% in 2002, or 11% to 19% of the combined area of these two managed land uses. Since this amount of bare ground was very high at each image acquisition, it is clear that this was not a random effect. As these pumice soils have a high erosion potential, leaving soils bare will result in more soil erosion and a greater potential for nutrient leaching to ground water. Much of the leached N will eventually reach the lake and reduce water quality. N loss from exotic forests is greatest in the 2 years following harvest and particularly where the site is root raked, wind-rowed and/or burnt (Dyck *et al*. 1985). Nutrient leaching will be exacerbated as a result of mineralisation of organic matter (Stockdale *et al*. 2002) following soil disturbance (e.g. root raking, cultivation) and/or herbicide desiccation of pastures (Betteridge *et al*. 2007).

Catchment-scale maps of land use and land management could be used by regional authorities to rapidly and cost-effectively compare current and past land use activities, as a tool to aid fine tuning of regional management plans. With good livestock statistics and water quality monitoring now available within the Lake Taupo catchment, it will become increasingly easy to determine the relationship between land use and management, and water quality. The previous mis-match of statistical boundaries for census and water catchments in this region made it impossible to do this in our study.

Although the 30 m pixel resolution of Landsat 5 and Landsat 7 images were not used to study change within paddocks on individual farms in this study, this possibility does exist and farmers should consider using such images for farm photos and making of maps within GIS, when developing farm plans.

Conclusions

Satellite imaging at a 30 m resolution provides a cost-effective means of assembling high quality resource data for 'whole-catchment' management planning and for 'within-farm' decision-making. Satellite data can be acquired retrospectively, and more frequently than data from more expensive aerial surveys. This time-sequence of the Lake Taupo catchment images showed only small changes in land use since 1975. However, the practice of cropping and pasture renewal with cultivation, and clear-cut harvesting of forests, may have a significant impact on water quality. In order to improve quality of Lake Taupo water, it may be necessary to recognise and respond to these practices that contribute disproportionately to N and other nutrient losses to the environment. Statistical data on stocking rates are important for interpreting the impact of land use on the environment, but satellite images cannot provide these data. Because boundaries used to collect livestock census data did not coincide with the Lake Taupo catchment boundaries, it was not possible to derive a more conclusive interpretation of how land use change may have contributed to increased N levels in ground water of farmed catchments.

Farmers, scientists and policy analysts can use satellite data for within-farm and for whole-catchment decision making and planning. These data are more readily available and come at a cheaper cost than aerial mapping data which, while providing slightly greater accuracy (but possibly more than required for many purposes), can often take several months for the mapping company to acquire.

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