Modelling Nutrient Loads to Better Manage Impacts of Urbanization in Tweed Catchment, New South Wales, Australia

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EXTENDED ABSTRACT

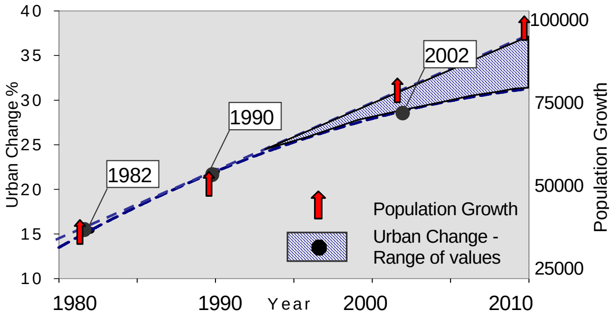
The Tweed catchment on the NSW Far North Coast was selected to examine historical land use patterns and to assess land use planning scenarios in terms of their potential impact on nutrient emissions. With the total population of 79,300 and an estimated annual population growth of 2.7% the Tweed Shire is one of the fastest growing local government areas along the NSW Coast. The land use patterns range from high-density urban and residential along the coast to low density rural and bushland in the upper reaches of the catchment. Rapid growth places the area under increasing pressure from development, which, in turn, adds to other already strong environmental pressures. The ability to assess nutrient emissions from the existing diffuse sources and those resulting from land use change is essential for planners to design environmentally sustainable development and for managers to focus limited resources to mitigate existing or potential inputs. The Tweed catchment was used as a pilot area to road test the assessment tools and the planning mechanisms developed within the NSW Comprehensive Coastal Assessment framework (CCA).

A fused satellite imagery classification method was used to document spatio-temporal changes in land cover and land use that have occurred in the catchment since 1982. The results show that urban change has affected approximately 1400 hectares in total, with the coastal fringes of the catchment experiencing the strongest growth, where urban areas increased by 6.5% over the study period. If the current trends persist, 31 to 36% of the area might be under development by the year 2010 (Figure 1).

The paper discusses changes in urbanization in the coastal areas of the Tweed Shire and the environmental impact of urban growth. The Long-Term Hydrologic Impact Assessment (L-THIA) model was used to predict changes in runoff and Non-Point Source (NPS) pollution from historical, current and proposed land uses in the catchment. The runoff volumes are predicted with the Curve Number (CN) method, which requires precipitation, soil type, vegetation cover, and management practice data. L-THIA requires land use classes from integrated image interpretation to estimate catchment emissions of total nitrogen (TN) and total phosphorus (TP). Modelling results provide a vital insight into the relative hydrologic impacts of different land uses and land use change over time. The assessment of over 20 hypothetical land use change scenarios shows that urban development can make a major contribution to nutrient exports, and emphasizes the need for best management practices in urban design. Results also highlight that overall nutrient emission may be minimized by preferentially accommodating urban development within areas where current land uses are associated with high nutrient export rates.

The assessment of nutrient loads and their impact on receiving waters can be used to raise community awareness of long-term pollution hazards and to support sustainable planning strategies. The use of GIS framework for testing of various urbanization options provides a means of deriving spatially distributed estimates and offers a platform for interpreting and synthesizing data from different sources.

Figure 1. Change in the urban areas of the coastal zone of the Tweed catchment extrapolated to 2010



1. INTRODUCTION

There is growing evidence suggesting that diffuse sources of pollution contribute substantially to downstream water quality problems. This, together with a rapid expansion of urban areas, necessitates a new approach to managing water quality at catchment and tributary scales. The purpose of this work was to estimate nutrient loadings to waterways resulting from the existing and changed land uses in NSW coastal catchments and to provide a tool to evaluate planning options and sustainability assessments. A GIS framework was used for interpretation of satellite imagery to provide contemporary land use classification and for development of catchment models. Nutrient loads were estimated using a modified Long-Term Hydrologic Impact Assessment (L-THIA). The broad scale model explicitly links land use type and change to nutrient emissions thus providing a predictive tool for planning. This is demonstrated through the analysis of land use change and hypothetical planning scenarios for the Tweed area in northern NSW.

2. LAND USE MAPPING AND URBAN CHANGE

2.1. Data and General Approach

Digital analysis of remotely sensed data was used to develop land use data suitable for assessment of nutrient loadings and detection of load changes due to land development in future. The land use change assessment in the Tweed catchment was conducted for period of 20 years (1982-2002). The temporal extent was constrained by the availability of the multispectral Landsat 4 data. A 10-year time increment was chosen as suitable for the analysis of land use change. Analysis of the satellite imagery started with an unsupervised classification, after which a supervised maximum likelihood classification within ERDAS Imagine software was performed (Civco and Hurd, 1999). A number of iterations within each classification step were typically conducted before the data was subjected to an exhaustive, manually controlled editing and verification process during which each classified area was compared with auxiliary data to determine the final land use class. In addition, roads and drainage, street directory or NPWS estate data were rasterized and incorporated into the land use theme to aid classification of unresolved areas not discernible after initial steps. This resulted in a preliminary set of broad land use classes.

For areas that experienced the fastest urban growth such as coastal fringes, all urban and commercial uses were first extracted by digitising aerial photographs, where available. An attribute table associated with the new urbanized vector layer was updated to indicate the year and the type of each urban polygon. The additional editing involved repeated comparisons with the Landsat imagery to ensure that all urban areas were included. The urbanized vector layer was then integrated into the land use classification model to extract urban areas from unresolved pixels and to refine the classification using a spatial modeler tool. In the spatial modeler tool conditional functions were developed to aid classification of unresolved pixels in urban polygons as an urban class, and therefore to improve the overall quality of the classification.

In the final step of the classification an attempt was made to enhance the resolution of built-up areas and delineate them into 3 classes representing different development densities: high, medium and low. Residential densities have major implications for planning and rating of development options as they usually indicate increasing percent of imperviousness in the catchment, which has a dominant effect on the volume and the timing of runoff. The following thresholds based on the percentage of imperviousness were selected to delineate different urban densities:

- Low Density Urban < 30%
- Medium Density Urban 30 – 50%
- High Density Urban > 50%

Due to large variations in the estimates of imperviousness, the threshold levels adopted here were somewhat arbitrary, however, they correspond with the figures generally adopted by planning authorities. The neighborhood density analysis (Tomlin, 1990) with a scanning window of 5x5 pixels was used to interpret homogeneity of the built-up areas. The scanning area was defined by two classes in the land use thematic layer: urban (excluding urban vegetation) and transport. It was assumed that those classes were the most homogenous and contributed exclusively to the level of imperviousness.

2.2. Trends in Land Use Change

The results of satellite imagery interpretation were used to document the spatio-temporal changes in land cover and land use that have occurred in the Tweed catchment since 1982. Figure 2 shows the expansion of built-up areas in the eastern part of the catchment. The urbanized vector layers for 1982, 1990 and 2002 periods are plotted over a 1-metre resolution digital aerial photography as a background to illustrate the landscape in the catchment. It is clearly visible that the foreshores of the catchment and the fringe of the lake were the major targets for development. The results indicate that over the last 20 years natural and semi-natural land uses have been gradually decreasing giving way to highly modified land uses such as urban residential and urban centers commercial/industrial, and transport (marked as urban high density in Figure 2).

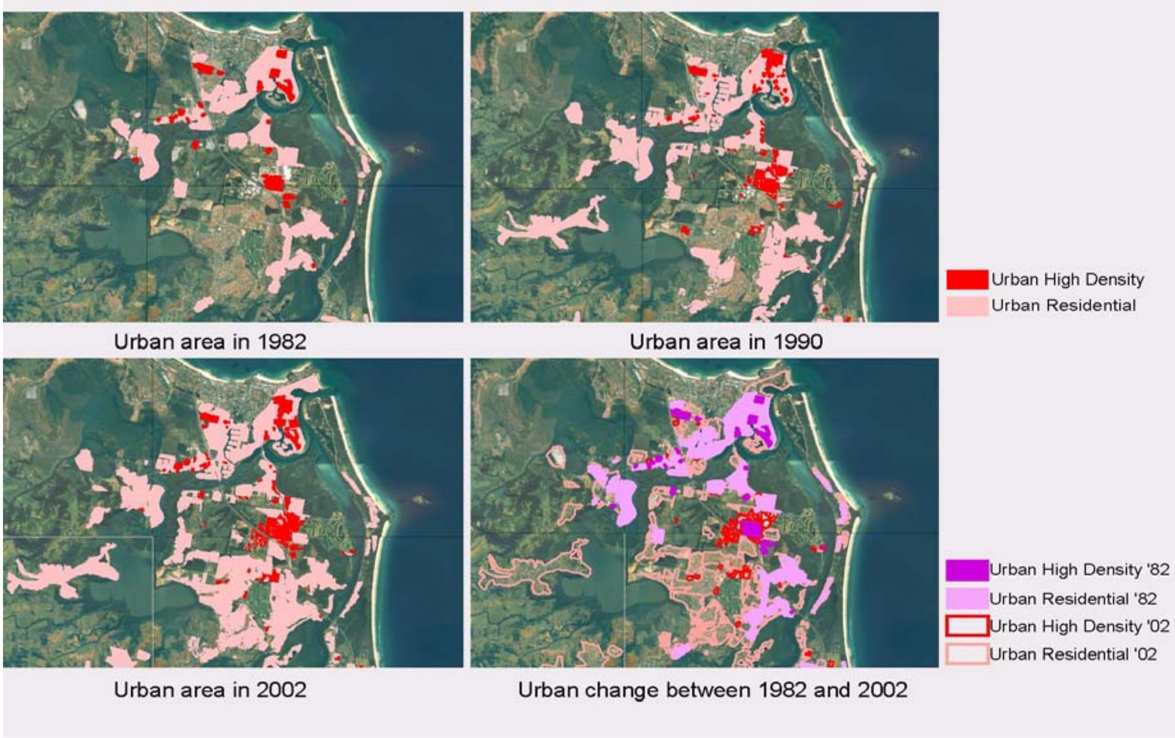


Figure 2. Distribution of developed land in the coastal area of the Tweed catchment

In 1982, less than 1200 hectares (0.9%) of the Tweed catchment was classified as urban while in 1999 and 2002 the urbanization reached 1900 hectares (1.4%) and 2500 hectares (2%), respectively. The total urban change affected approximately 1400 hectares. Although the proportion of urban land use is relatively small the rate of increase in urbanized land is significant and concentrated in specific areas. The coastal fringes and the area in close proximity to Cudgen Lake experienced quite staggering development growth exceeding 13%. To assess the trend in land use change in the area depicted in Figure 2, land use classes were aggregated into just 3 major groups, that is: natural, rural and urban. The analysis showed that between 1982 and 2002 the urban area experienced a strong growth resulting in an increase in built-up areas at an average rate reaching 0.7% per year. In total, over the study period, more than 850 hectares of bushland and rural land became urban.

The observations of land use change for 1982, 1990 and 2002 were then projected into the future to show the development trends (Figure 1). The results indicated that if the current trends persist, 31 to 36% of the area might be under development by the year 2010.

The projected increase in built-up areas may have a profound impact on rainfall-runoff relationships in the catchment primarily because of the likely change in the level of imperviousness and the amount of runoff generated, which in turn would have a direct impact on pollutant loads.

3. MODELLING CATCHMENT LOADS

L-THIA model (Lim et al., 1999) was selected to link nutrient emissions to land use changes and to predict annual nutrient loads. The model was developed as a GIS application and requires ArcView software to run. L-THIA was originally developed as an impact assessment tool, with an objective to assess the impacts of alternate development plans and land use change scenarios (Harbor et al., 2000). Outputs from the spatially distributed model (25-m grid) provide a means for comparative assessments within a study area and for identifying areas within a catchment that are likely to contribute elevated levels of pollutants.

3.1. Model Requirements and Input Data

Runoff volumes

The model has moderate data requirements. The basic input consists of soil, precipitation and land use data. Runoff volumes are predicted with the curve number (CN) method, which uses commonly available information, such as soil type, cover and hydrologic conditions, to estimate runoff (USDA, 1986). The approach involves use of an empirical formula to estimate total excess rain for a storm or a long-term data series. The method has been applied to a wide range of catchments and climatic conditions for estimation of runoff volumes in ungauged areas in the United States (Browne, 1999, Knisel, 1980). It is one of the few methods providing means for estimating runoff change due to land use change. CN values can vary from 0 to 99, with higher values representing higher runoff potential. L-THIA associates CN value for each grid cell based on the soil properties and land use/cover type. To account for often observed variations in CN values from storm to storm the model employs a concept of antecedent moisture condition (AMC). The AMC defines the initial moisture condition of the soil prior to the storm event and it is expressed as an index of the total 5-day antecedent rainfall (McCuen, 1982). AMC II was used for conservative estimates of runoff volumes in the Tweed catchment. It represents average moisture conditions with the dormant season rainfall (5-day) averaging between approximately 12 and 28mm, and the growing season rainfall between approximately 35 and 53mm.

Hydrologic Soil Groups (HSGs)

The model requires a soil grid layer classified into hydrologic soil groups to determine the runoff curve numbers. HSGs indicate the minimum rate of infiltration obtained for bare soil after prolonged wetting, and the rate at which water moves within the soil, which, in turn, depends on the soil profile characteristics (USDA, 1986).

Soils in NSW have not been classified into HSGs and information on soil permeability and saturated hydraulic conductivity is not readily available. Therefore HSG classes (A,B,C,D) had to be assigned from the relationship between the range of available soil properties and HSGs (Table 1). Coverages of soil landscapes and the associated databases containing detailed subsoil landscape properties were used to develop linkages between often varying levels of the soil data to assign the soils with a particular HSG class. Soil limitation information for soil landscapes such as poor drainage, permanent high water table, high permeability, and shallow soil profile were also taken into account when assigning soil to HSGs.

Table 1. Soil properties used to define Hydrologic Soil Groups (HSGs)

Soil properties	A	B	C	D
Runoff Potential	Low			High
Infiltration Rate	High	Moderate	Low	Very Low
Soil Depth	Deep	Moderately - Deep		Permanent high water table, clay pan or clay layers at or near the surface, and shallow soils over nearly impervious material
Drainage	Excessively Drained	Moderately well – Well drained	Layer that impedes the downward movement of water	Very poor
Soil Texture	Sand or Gravel	Moderately fine – Moderately coarse	Moderately fine – Fine	Clay with high swelling potential
Rate of Water Transmission	High	Moderate	Low	Very Low
Ks* mm/ hour	>7.62	3.81 - 7.62	1.27 - 3.81	0 - 1.27

*Saturated hydraulic conductivity (Ks)

Event mean concentrations

The model employs a simple formula in which the nutrient load is a product of runoff volume and the concentration of the pollutant in the runoff water. As land use is a major determinant in computation of nutrient loads, L-THIA comes with a predefined set of event mean concentrations (emcs) compiled from published sources and studies conducted overseas and representative of major land use classes.

To provide a more relevant and site specific estimate of nutrient loads for coastal catchments in NSW, a new set of emcs was determined. All land use classes were aggregated according to the perceived capacity to generate nutrients. Those land use categories were then matched with the reported data for the purpose of assigning emcs. The emcs for urban areas were derived predominantly from the results of monitoring studies reported by Fletcher *et al*. (2004). In this report water quality data from a wide variety of sources was reviewed and synthesized to provide a comprehensive emc guide for a range of land uses and climatic regions within NSW. The mean values from the wet weather range recommended by Fletcher *et al*. (2004) were assigned to each of the aggregated land uses. These values were then compared with the site-specific studies where available and, if necessary, further refined to address the differences in urban densities and other environmental and management factors. Table 2 shows the final set of emcs used to model nutrient loads for Tweed and other coastal catchments in NSW.

Table 2. *Emc*s used for nutrient load simulation

Land Use Class	*emc* [mg/L]	
	TN	TP
Agriculture/Cropping	4.4	1.3
Agriculture/ Improved Pasture	1.0	0.5
Urban Low Density; Caravan Park; Urban Park & Golf Course	1.8	0.25
Urban Medium Density	2.2	0.7
Commercial/ Industrial/ Urban High Density; Bare land	3.3	0.7
Transport & Communication	2.0	0.5
Conservation/ Bushland; Unimproved Pasture; Sand/ Beach	0.7	0.01

The nonpoint module of the model was run for each catchment with the set of default emcs. Then the results were recalculated with the new emcs, and the pixel output data aggregated to a subcatchment level. The final outcomes of the model are available either as nutrient load per pixel or total load per land use.

3.2. Estimation of Nutrient Loads for the Tweed Catchment and Scenario Testing

Nutrient emissions, simulated with L-THIA, vary considerably with the size of the drainage area and the composition of land uses. Lower Tweed Estuary, the largest river system in the region, is the major nutrient contributing area estimated to generate more than 103 tons/yr of TN and 28 tones/yr of TP. It is representative of mixed land uses with a considerable proportion of cropping, grazing and residential uses dominating over native vegetation and unimproved pasture areas. The highest nutrient loads per unit area were detected within the quickly urbanizing coastal area of the catchment shown in Figure 2. In the last 20 years the area has experienced an almost three-fold increase in urbanization leading to higher runoff and nutrient generation (Figure 3) and thus increasing the risk of eutrophication in receiving waters. Robson *et al.* (2005) modelled eutrofication response of the Tweed River estuary and other coastal lakes to changed nutrient loads estimated by this project. Increasing nutrient loads resulted in greater concentrations of phytoplankton (chlorophyll-a) that frequently exceeded recommended trigger values for estuaries in south-eastern Australia.

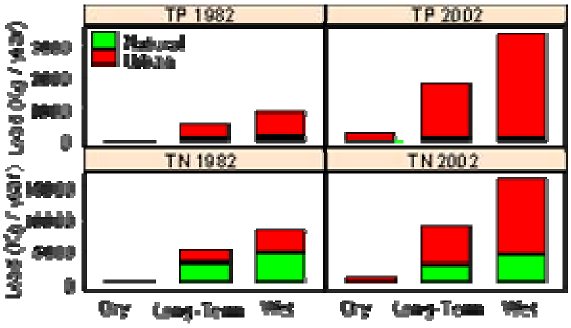


Figure 3. Simulated nutrient loads for land use conditions in 1982 and 2002. (*Long-Term-10-y average rainfall, Dry– driest year, Wet– wettest year in the series)*

Actual loads are strongly influenced by temporal changes in climatic patterns so simulations were conducted for a below average rainfall year, long-term average rainfall conditions and an above average rainfall year. Simulations for extreme rainfall conditions (dry or wet) should be treated with caution. Under these extreme conditions, other factors such as erosion rates and rainfall erosivity and magnitude could be governing the nutrient exports. However, these results can be used to better understand the likely variations in the estimated loads as well as to provide an insight into the level of uncertainty associated with the loads expected while using either modelled or measured load data.

The model was also used to simulate exports of nutrients under land use hypothetical scenarios for 21 sites proposed in the considered region (Figure 4).

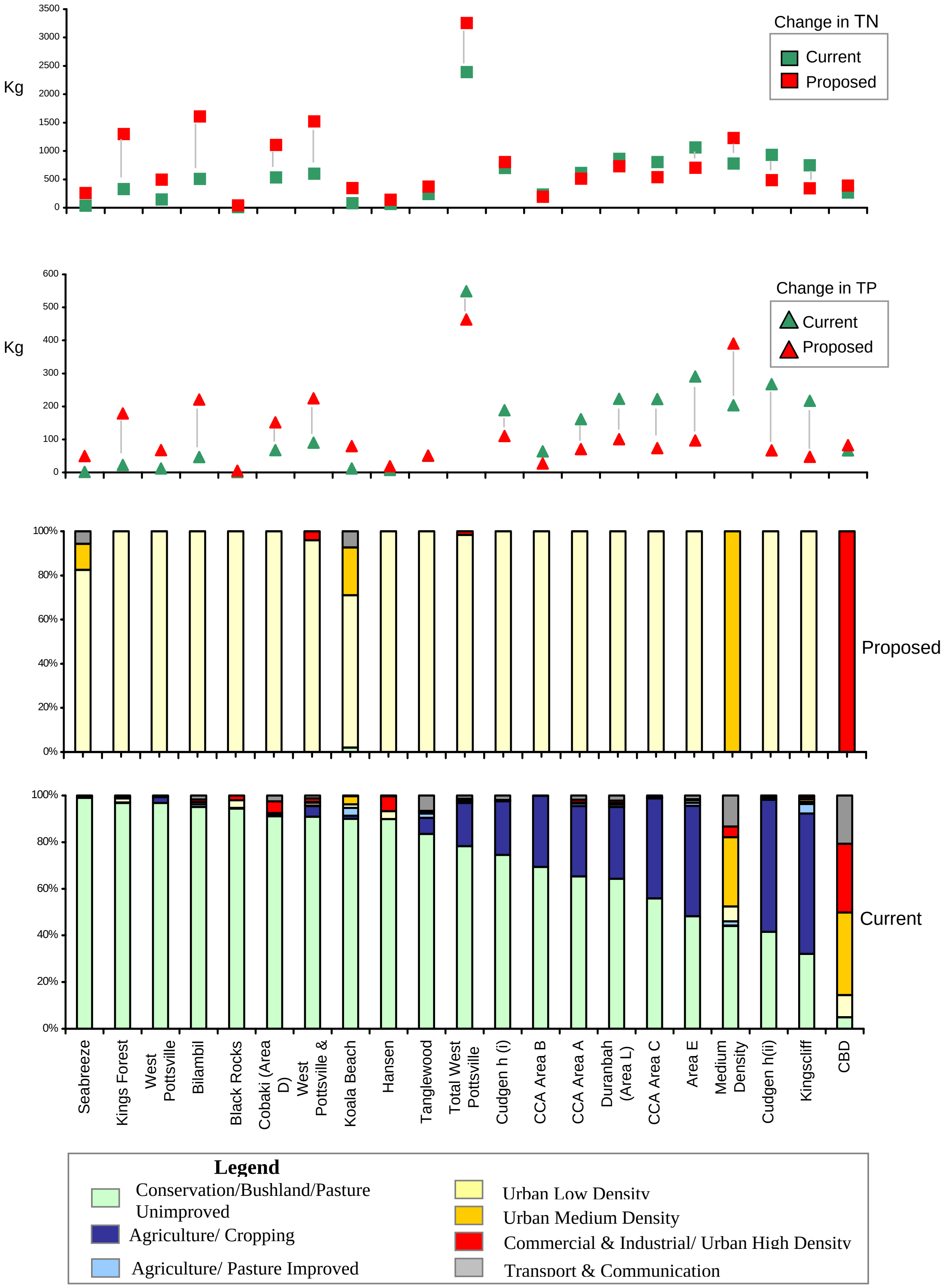


Figure 4. Estimates of TN and TP exports for hypothetical land use scenarios in the Tweed catchment with the sites ranked by Conservation/Bushland

All scenarios tested involved land developing with a varied degree of urbanization. The size of the proposed developments varied from approximately 21 to more than 560 ha.

Figure 4 shows estimates of nutrient export potential for the current and modelled land uses in each scenario. The scenarios are ordered by the proportion of Conservation/Bushland in each area. It is clearly noticeable that for the scenarios where currently the natural land uses dominate (up to 80% Conservation/Bushland), phosphorus and nitrogen loads are expected to increase following urbanization. The assessment reveals that, on average, there will be a 3-fold increase in TN load and a six-fold increase in TP load in these areas. The largest relative increase results from the development of the Seabreeze, while in absolute terms Bilambil Area exhibits the largest increase in nutrient loads after development. For scenarios with mixed land uses, change in nutrient loads is less profound. Despite the fact that reduction in nutrient loads may occur in areas predominantly used for agriculture, the predicted nutrient and in particular TN loads are still very high.

4. CONCLUSIONS

Catchment modelling such as presented in this study is often the only way to assess potential nutrient loadings due to existing land use distributions and alternate planning scenarios, especially at a regional or catchment scale. For the majority of NSW catchments relevant monitoring data are either unavailable or not representative of the required scales for decision-making (i.e. sparse coverage and poor representation of events). The tidal impact and the fact that most stream gauging stations and water quality monitoring locations are located well upstream leaving large portions of the catchment ungauged and therefore difficult to assess, are additional complicating factors in coastal catchments. Areas close to the coastline are under most stress from development and dynamically changing land uses. Historical trends in land use change provide a critical context for current and future land use decisions.

Nutrient loadings must be considered in relation to the vulnerability of the receiving waters to those loadings. A companion CCA project (Robson *et al.*, 2005) has simulated the response of receiving waters (coastal lakes and estuaries) to the changed nutrient loadings and thus has determined the resilience of receiving waters to these loadings. This way an environmental attribute such as eutrophication status can be systematically incorporated into integrated regional planning processes. The land use changes are linked to altered nutrient emissions through catchment modelling which in turn are linked to effects in coastal lakes and estuaries through vulnerability weightings. Opportunities now exist to consolidate the information and modelling described here within a user-friendly, regional, planning and priority setting tool. Work has been undertaken to develop CERAT (**C**oastal **E**utrification **R**isk **A**ssessment **T**ool) that will help assess and minimize eutrophication impacts in our coastal waterways by linking land use change and diffuse nutrient loadings with the resulting eutrophication status of the waterbody.

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