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A framework for developing an environmental accounting system for freshwater ecosystem services in the Waikato Region

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Confidential Report

A framework for developing an environmental accounting system for freshwater ecosystem services in the Waikato Region

Richard T. Yao and David J. Palmer

Land use, land cover and freshwater availability
in the Waikato region

Report information sheet

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Photo description and credits	• Photos of the Aratiatia hydropower dam in the Waikato's Taupō District. Hydropower is the largest source of renewable energy in New Zealand. https://www.hukafallscruise.co.nz/aratiatia-dam-and-rapids/ • Pastoral dairy farming and exotic forestry are dominant productive land use in the Waikato and Bay of Plenty regions. https://www.waikatoregion.govt.nz/environment/land-and-soil/land-use-in-the-waikato/ https://www.boprc.govt.nz/environment/land/forestry • The Waikato region is renowned for its intensive pastoral dairy farming due to its favourable climatic condition. Dairy farming has also been found to have adverse effects on water quality and therefore environmentally sustainable farming is advocated by groups who participate in water-based recreation. https://fishandgame.org.nz/about/f-and-g-position-statements/dairy-farming-and-the-environment/

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Executive summary

The Waikato Regional Council (WRC) is undertaking a long-term project to assess ecosystem services (ES) from freshwater resources in the Waikato Region. This project contributes to the WRC Regional Policy Statement to ensure that the range of ES associated with natural resources are recognised, maintained and enhanced to contribute to human wellbeing in the region. The first two phases of this project involved a desktop assessment of selected freshwater bodies (rivers, streams, lakes, and wetlands, including terrestrial geothermal areas) in the Waikato and Waihou river systems to identify, quantify and value (where possible) the freshwater ES. The third phase assessed 57 ES provided by the rivers and streams in the region's Ohinemuri catchment. This project extends previous research by evaluating the impact of land-use change on water availability related ES in a river catchment in the region.

This project

The objective of this study (Phase 4) was to evaluate the impacts of land-use change on five water availability related ES consisting of water yield, hydropower generation, quick flow, local recharge and baseflow. The team identified an area in the Waikato region where a significant shift in land use and land cover occurred. Using literature review and GIS technologies we found that a substantial area of planted forests and deer farming were converted to a more intensive land use (i.e., dairy farming) in the Upper Waikato catchment. We also found eight hydropower stations operating in this catchment. By applying spatial modelling techniques to analyse biophysical and land cover data, we have identified an 838,505-ha river catchment in the region that suits the assessment of the five ES above.

Land-use and land cover (LULC) maps were constructed for the years 2001/02 and 2018/19 to evaluate land-use change impacts on the five freshwater ES in those years. The study site was subdivided in two ways: (1) eight overlapping[1] sub-catchments with each assigned to a hydropower station; and (2) nineteen different LULC classes, which can mainly be categorised into *productive* (dairying, exotic forests, sheep, beef and cattle farming, and deer farming), *natural* (indigenous forest, herbfield and tussock grasslands) and *built environment* (built-up areas, transport infrastructure).

To quantify the five ES over time, we used two spatial models, *Water Yield* and *Seasonal Water Yield,* from the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) platform. InVEST is a US-developed open-sourced software platform that provides a suite of spatial models to map and value the goods and services provided by nature. To run the InVEST models, we have constructed climatic, river, hydropower, LULC classes, soil and water demand data sets for the study area.

LULC maps for each sub-catchment were created that characterise land cover for the two study periods. The impacts of land use change on the five ES were quantified for each sub-catchment using the InVEST platform which accounts for biophysical and climatic factors as well as volume of water used by the different LULC classes. To compile and present the estimates from InVEST across the different LULC classes, we have constructed two pilot ecosystem accounts (extent and capacity accounts) to illustrate the water flow regulation impacts of land-use change.

Key results

Comparing 2001/02 with 2018/19, areas of dairying farms in the full catchment increased by 10% (81,668ha), whereas forestry, sheep, beef and cattle farming areas decreased by 9% (73,327ha). Seven out of eight sub-catchments had reduced forestry areas from 12% to 19%. In the Aratiatia sub-catchment, the forestry area increased by 9% (5,938ha) and dairying increased by 83%(1,518ha). In the sub-catchments of Arapuni and Ohakuri, forestry respectively decreased by 15% (32,824 ha) and 15% (16,934 ha), while the dairying respectively increased by 116% (62,866ha) and 116% (33,514ha).

[1]It is assumed this will not any substantial impacts on the study results because the flow of water in each sub-catchment is independent from other sub-catchments as hydropower plants do not consume water but only regulating the flow so the overall volume of water flowing in the longer term is about the same across the sub-catchments.

Results from InVEST modelling show how the five indicators of freshwater ES were impacted by the shift to more intensive land use over the 17-year period. Aratiatia, the sub-catchment with the lowest conversion rate to more intensive land use, had the smallest reduction in water yield during the wet year (only 0.01% reduction compared with 0.08% to 0.13% in other sub-catchments). Aratiatia also had the smallest increase in water consumption and the lowest reduction in hydropower production. This result illustrates a negative impact of increasing land use intensity which results to a change in hydrological factors and an increase in anthropogenic water use (or increase in water consumption due to land use intensification).

Estimates from the Seasonal Water Yield model (which does not account for increased water consumption from dairying), suggest that Aratiatia increased baseflow and local recharge in both wet and dry years while the seven other sub-catchments indicated a decrease in those water-related ecosystem services. The quickflow or floodflow in Aratiatia was also the least affected by land-use change. Overall results from the Seasonal Water Yield modelling found a more stable provision of water flow regulation services in the sub-catchment with the least conversion to more intensive land use.

The creation of two pilot ecosystem accounts allowed us to estimate the impact of land-use change on the entire study catchment across the 19 major LULC classes. The ecosystem extent account found that while dairying areas increased by 84%, exotic forests and sheep, beef and cattle farming areas decreased by 18% and 14%, respectively. The ecosystem capacity account (which excludes hydropower generation values) calculated that, overall, a shift to more intensive land use was associated with reduced provision of the 4 water availability related ES. For example, water yield was reduced by 0.09% (793,024 m^3) and 0.01% (76,592 m^3) in the wet and dry years, respectively. Although percentage changes in water volume were all less than 1%, the volume of water reduction in m^3 for the whole catchment was substantial with baseflow reduced by 1.1 million m^3.

To validate our water yield estimates, we compared our results from the InVEST Water Yield model with the 2018 water yield data generated by New Zealand validated WATYIELD water balance model (Fahey et al. 2010). InVEST estimates of water yield varied little from the WATYIELD model estimates. In other words, InVEST estimates are somewhat consistent with WATYIELD.

This study has developed and applied a new framework to quantify land use change impacts on five water availability related ES. Analysis was undertaken at the sub-catchment level to evaluate the impacts on the provision of water flow related ES. Analysis was also undertaken by LULC class which enabled the creation of pilot ecosystem accounts for the 19 LULC classes under three different modelling scenarios: (1) impacts of LULC change between the two study years (2001/02 and 2018/19); (2) impacts of the change in LULC in the wet year (2001/02); and impacts of LULC change in the dry year (2018/19). Results were summarised systematically for informing decision-making processes. This new assessment framework is illustrated as a flow diagram in Appendix F.

Implications of results for the client

This study highlighted how land-use change might impact the provision of water, a significant ecosystem service in the study area. It demonstrates operationalisation of the concept of ecosystem services as being advocated for in (Gardiner and Huser 2017). The web map with the associated database on freshwater ecosystem services assessments on the WRC website may be updated with this report.

This report demonstrates the connection between the region's environment, economy and society, which may provide policy discussion points on sustaining and enhancing freshwater resources and their contributions to human well-being. The report could help inform the reporting of Waikato Progress Indicators and WRC's work with national government agencies on the healthy waterways programme and the National Policy Statement for Freshwater Management.

Further work

This research has developed a good understanding of water availability assessment-related ES. We have interacted with fellow environmental economists, environmental accountants, hydrologists, and the hydro-power generation industry who provided valuable insights that helped us quantify and report water availability related ES values. In the quantification process we found a few other spatial models that can also be used to quantify similar water availability and water quality related ES. We, therefore, proposed that a future work should assess both water availability and water quality related ES in the region using InVEST and other relevant models. Models in this space are continuously being improved, so applying them in a future project would allow for better quantification of freshwater ES as well as identify the values that are more suitable for informing specific decisions, accounting for or reporting of freshwater ES values. In addition, it would be helpful to compare InVEST model estimates with at least three other spatial models such as LUCI (Land Utilisation Capability Indicator), SWAT (Soil & Water Assessment Tool) and WATYIELD Water Balance model to demonstrate robustness in estimating the physical flow of ES and their corresponding values. Such comparison will include model calibration which may help in validating estimated ES values.

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Introduction

Freshwater related ecosystem services (ES) are vital to human well-being and have received more attention than any other ES category (Seifert-Dähnn, Barkved, and Interwies 2015; Keeler et al. 2012). Freshwater ecosystems provide a wide range of direct and indirect services to human society, including consumptive (drinking, residential, agricultural, and industrial usage) and non-consumptive (power generation and transportation) use (Baillie and Yao 2015; Aneseyee et al. 2022; Aylward et al. 2005). However, the provision of freshwater related ES can be affected by land use and vegetative land cover surrounding freshwater ecosystems (Esse et al. 2021; Ahiablame et al. 2017).

The material benefits that flow to our primary industries from our freshwater ecosystems are considered the most important because they directly contribute to economic growth, for example by providing additional employment and export revenue. Quantifying the value of these material benefits is straightforward because they are observed in market transactions. However, the value of environmental benefits such as the availability of freshwater resources that contribute to the general public's well-being remains poorly understood; these benefits are rarely reflected in market prices. These environmental values include the benefits derived from collecting food in the wild for free (e.g. watercress), water flow regulation, education, recreation, aesthetics and the maintenance of the integrity of our natural environment (Brauman et al. 2020). This situation has resulted in the value of marketed goods from our primary sectors acting as the key driver in land-use decisions while the wider environmental and cultural benefits from our freshwater resources are overlooked and heavily discounted (Khan and Zhao 2019; Grizzetti et al. 2016). However, with the development of techniques to quantify and more systematic ways of presenting and accounting for these values, there is an opportunity to make these benefits more visible in policy discussions and decision-making.

Studies have evaluated land use and land cover change (LULC) impacts on water quality and quantity. Rivers, streams and lakes receiving water from agricultural land typically have a greater concentration of nutrients (i.e., nitrate nitrogen and phosphorous) than those receiving water from forested areas (Kibena, Nhapi, and Gumindoga 2014; Ding et al. 2015; León-Muñoz et al. 2013). Change in LULC influences hydrologic functions by altering the patterns of evapotranspiration, surface runoff, water infiltration and retention while also changing the timing and volume of water available for hydropower production (World Commission on Dams 2000; Ennaanay 2006). In New Zealand, LULC change (i.e. pasture to forest - afforestation) has been found to decrease water availability/yield (Davie and Fahey 2005; Blaschke, Hicks, and Meister 2008). Woods et al. (2010) indicated that conversion of exotic forestry to pastoral agriculture in a Waikato River catchment (a different catchment from our catchment study site) would increase the total volume of flood run-off. However, there has been no study yet on the impact of land-use change on the value of hydropower generation in New Zealand. To the best of our knowledge, this is the first New Zealand study that evaluates the impacts of land-use change (between forestry and pastoral agriculture) on hydropower generation and other water availability indicators.

This study aims to develop a framework to quantify freshwater values that may be impacted by land-use change and enable their representation in policy discussions and the development of freshwater environmental/natural capital accounting system for the Waikato Region. The following activities have been undertaken:

a) Literature review on the value of freshwater ecosystems to society focusing on the spatial quantification of those values;
b) Identification of the key trends in the study area on land-use change and evaluate their association with water availability;
c) Collection of data and construction of spatial layers for running spatially models that quantify freshwater ES values due to land-use and land cover change; and
d) Using the results of spatial modelling, discuss how those outputs can be used to start the discussions and reporting of water availability ES values in the region.

Background

Over the past two decades, the Waikato region experienced two major types of land-use change:

a) Conversion of planted forest areas to pasture (mainly dairy farming) (Woods et al. 2010); and
b) Conversion of dry stock farming (e.g. sheep and beef farming, deer) to dairy farming.

Between 2002 and 2008, about 29,000 hectares of forestry land were converted to pasture in the Upper Waikato catchment (Archer, Palmer, and McKenzie 2019). This more intensive pastoral land use (i.e., dairy farming) contributes significantly to GDP growth and employment generation in the region (Destremau and Siddharth 2018). However, the higher stocking numbers and greater inputs of fertiliser (River & Catchment Services Group and 2010 2011) required to support dairy land use can contribute to a decline in water quality, increased run-off of nutrients (e.g. nitrogen and phosphorous), increased soil erosion and flooding (Woods et al. 2010; River & Catchment Services Group and 2010 2011).

The Waikato Regional Council (WRC) plans to restrict land use change through the Healthy Rivers Plan Change 1 which states that "…*land use change consent applications that demonstrate an increase in the diffuse discharge of nitrogen, phosphorus, sediment or microbial pathogens will generally not be granted. Land use change consent applications that demonstrate clear and enduring decreases in existing diffuse discharges of nitrogen, phosphorus, sediment or microbial pathogens will generally be granted*" (Waikato Regional Council 2016).

Studies have examined the impact of land use change on water quality (e.g. (Trodahl et al. 2017), but studies on impacts on water availability has been limited (e.g. Woods et al. (2010)). We also found that studies on water availability in New Zealand often do not use an ES lens (e.g. (Fahey et al. 2010)). Hence, in this Phase 4 study, we investigate land use change impacts on water availability using an ES lens.
In the reports from the previous phases of this long-term research project, we provided key recommendations. In Phase 1, we stated that WRC would need to determine the scale of the next sub-catchment ES assessment based on environmental issues of interest. In Phase 2, we highlighted that the estimated values of ecosystem services from major rivers and streams in the region should be refined and integrated into a cohesive environmental accounting system to enable the representation of their non-market ES values as well as ES physical quantities in policy. In Phase 3, we suggested that the quantification of water availability (i.e., water yield) should be expanded to account for the seasonal flows, especially during the high rainfall winter months and the dry summer period.

The "Our freshwater 2020" report (New Zealand's Environmental Reporting Series) recommended that knowledge gaps in our freshwater environment should be addressed by: (1) understanding and quantifying the benefits of freshwater, including on wellbeing; and (2) improving our understanding of the pressures on freshwater and their causes, including how they interact and intensify in places and over time.

To address the above recommendations from the three completed project phases and those from Our freshwater 2020 report, the Phase 4 of the project (or this project) focused on modelling the impacts of land use change on water availability related ES values in a Waikato River catchment over two periods -2001/02 and 2018/19.

Methods and Data

Methods

Impacts of land use in the catchment was measured for 2001/02 and 2018/19 and the change quantified. The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) platform was then used to quantify the impacts on water availability given land use change. InVEST is a platform that provides a suite of spatial models for exploring how changes in ecosystem quality and/or features are likely to alter the flow of ES that are realised by society (Sharp, Fisher, and Lacayo 2020).

We applied two models from the (InVEST) platform: *Water Yield and Hydropower Generation* and *Seasonal Water Yield*. To the best of our knowledge, this is the first New Zealand application of the two InVEST models. To run the

InVEST models, we constructed climatic, river, hydropower, land use / land cover classes, soil and water demand data for the study catchment.

InVEST Water Yield

Water yield is broadly defined as the amount of water "produced" by a watershed or a catchment. It is usually referred to as the difference between precipitation and evapotranspiration. However, there are several factors to consider when modelling water yield. To calculate the annual water yield in the study catchment and in the sub-catchments, we used the InVEST Water Yield model (Sharp et al. 2018). The Water Yield model also has an extension model that calculates hydropower production. We utilised the InVEST Water Yield and Hydropower Valuation model to spatially quantify the changes in water yield, consumptive water use and hydropower generation in the study catchment.

This spatial analysis in InVEST is undertaken on a per pixel basis. Each pixel equates to 15m x 15m area land. The first component of the InVEST Water Yield model quantifies water yield based on the amount of water running off each pixel. Water yield is the amount of rainfall minus the proportion of this water that undergoes evapotranspiration. The model does not distinguish if water comes from either surface, subsurface or baseflow, but generally assumes that water yield for each pixel is derived from one these channels (Sharp, Fisher, and Lacayo 2020). The model then sums all water yield estimates per pixel for each sub-catchment. The pixel-based calculations enable the variation in climatic and biophysical factors to be accounted for across the study area (for example, soil type, rainfall, land cover and vegetation). The calculations for this component do not include anthropogenic uses of water such as domestic water supply and stock drinking water.

The second model component estimates consumptive water use per pixel. For each pixel, it considers the volume of water withdrawn (m^3/year), including anthropogenic use. The water withdrawn varies by LULC class as reported in the water demand column in Table 1. Values in the water demand column represent simplified consumptive water use by LULC in the catchment and are expressed in m^3/ha/year (Sharp, Fisher, and Lacayo 2020). Most parameters were derived from Baillie, Yao, and Palmer (2020). The parameter for water demand for dairy farming was calculated based on average total water use in selected Waikato dairy farms estimated in Higham et al. (2017), and an average stocking rate of 2.8 cows/ha from Journeaux (2020). The average water demand for built-up environment per hectare was calculated using StatsNZ's meshblock data on the population of usual residents and the average daily consumption of water in the City of Hamilton (Statistics New Zealand undated; Hamilton City Council undated) .

The third component quantifies the realised water supply. This looks at each pixel in terms of the water volume (m^3/year) that is contributed from the water yield model and water volume consumed based on LULC class. Therefore, each pixel is either a "contributing" pixel, which provides water for hydropower generation or a "use" pixel that provides water for other consumptive use. Therefore, this assumption indicates that "use" pixels will not provide water for downstream use (e.g. hydropower).

Per-pixel estimates of water yield, consumptive water use, and realised water supply are compiled spatially within InVEST and used to quantify the impacts of LULC change on the change in hydropower generation for each sub-catchment. For further details of the water yield spatial equations and hydropower valuation calculations, please refer to the InVEST Manual (Sharp et al. 2018).

Nine data sets were constructed to apply the InVEST Water Yield model in the study catchment (Table 2). The construction format of the annual average precipitation and potential evapotranspiration (PET) data long-term average climate data was based on Wratt et al. (2006). The data was reprojected from New Zealand Map Grid (NZMG) to New Zealand Transverse Mercator (NZTM) and resampled to a 15-m cell size resolution. The rainfall and PET data specific to the years 2001/02 (July to June) and 2018/19 (July to June) were from NIWA's daily Virtual Climate Network (VCN) Station data. VCN data is daily data on a 5-km point grid across New Zealand. We extracted VCN data for the study catchment, averaged the data across the year, and spatially interpolated the data using Inverse Distance Weighting (IDW) to a 15-m cell size resolution. This provides the InVEST Water Yield model with long-term average rainfall and PET, and specific rainfall and PET data for 2001/02 and 2018/19 as consistent 15-m cell size resolution rasters.

Root restricting layer and plant available water content (PAWC), was developed from the Fundamental Soil Layers (FSL) (LRIS 2010). FSL were also used to develop PAWC with values from zero to one. Root restricting layer was developed from the Potential Rooting Depth (PRD) layer.[2] PRD describes the minimum and maximum depths to a layer that may impede root extension. Such a layer may be defined by penetration resistance, poor aeration or low available water capacity. These rooting depth classes are described in detail in Webb and Wilson (1995) and Griffiths (1985).

The LULC rasters for the years 2001/02 and 2018/19 were developed based on Land Cover Database v.5.0 (LCDB5) layer (Landcare Research 2020) and Agribase enhanced land cover and land use data provided by WRC (Agribase: https://www.asurequality.com/our-solutions/agribase/) representing the summer periods of 2001/02 and 2018/19. Because we wanted to improve the detail of the information for LULC classes, we incorporated the LULC classes of dairy dry stock, dairying, deer, sheep, and sheep and beef from the surveyed data of Agribase into LCDB5, therefore creating hybrid LULC maps for the two study periods.

In conjunction with LULC data, the biophysical table provides the basis for estimating water yield. This includes landcover types, the plant evapotranspiration coefficient (Kc) factor associated with each landcover, and the maximum rooting depth for each landcover. We estimated these parameters and coefficients from broad habitat classes by matching these class descriptions with those in Madgwick (1994), Canadell et al. (1996), Allen (1998), and Sharp, Fisher, and Lacayo (2020). The Kc factor was developed from the 8-day averaged Moderate Resolution Imaging Spectroradiometer (MODIS) 500-m resolution data MOD16A2GF for PET and ET (Running et al. 2019). Data were averaged across each year, and the LULC polygon classes used to capture the PET and ET values for each class. Kc was calculated as the ratio of PET to actual evapotranspiration (AET) per LULC class.

To identify the different sub-catchments, we used the River Environment Classification (REC) data (Snelder, Weatherhead, and Biggs 2004). The sub-catchments were developed using a 15-m cell size resolution digital elevation model (DEM) (Columbus, Sirguey, and Tenzer 2011) and the InVEST module "DelineateIT" (Sharp, Fisher, and Lacayo 2020). The seasonality constant (Z) was estimated as $0.2 * N$, where N is the average number of rain-days (> 1-mm) per year over the study period (Donohue, Roderick, and McVicar 2012; Hamel and Guswa 2015), giving a value of 28 for Z. We present in Table 1 the list of parameters and coefficients used in the Water Yield's biophysical and water demand tables.

[2] https://lris.scinfo.org.nz/layer/48110-fsl-potential-rooting-depth/

Table 1. Parameters and coefficients in InVEST Water Yield's biophysical and water demand data tables.

Land use code	Land use description	Vegetation code (1=yes, 0=no)	Rooting depth* (mm)	Plant evapotrans-piration coefficient (Kc 2001/02)	Plant evapotrans-piration coefficient (Kc 2018/19)	Water demand** (m^3/ha/year)
1	Broadleaved indigenous hardwoods	1	800	0.705	0.671	0.3
2	Built-up areas	0	500	0.344	0.332	1474.5
3	Dairy dry stock	1	600	0.721	0.649	74.4
4	Dairying	1	600	0.720	0.654	115.6
5	Deciduous hardwoods	1	1100	0.711	0.675	0.3
6	Deer farming	1	550	0.704	0.629	37.1
7	Exotic forests	1	1100	0.677	0.638	0.3
8	Fruit orchards and vineyards	1	1000	0.723	0.674	15.0
9	Herbfield and tussock grasslands	1	400	0.699	0.610	0
10	Indigenous forest	1	1600	0.679	0.632	0.3
11	Transport infrastructure	0	-1	0.294	0.281	0
12	Permanent snow and ice	0	-1	0.300	0.300	0
13	Sheep, beef and cattle farming	1	550	0.701	0.635	37.1
14	Short-rotation cropping	1	400	0.690	0.612	34.6
15	Shrublands	1	1000	0.666	0.616	0.3
16	Sand, gravel, rocks	0	-1	0.839	0.769	0
17	Vegetable and flower production	1	300	0.700	0.604	20.0
18	Water	0	-1	0.961	0.955	0
19	Wetlands	1	150	1.143	1.098	0

*Note 1: InVEST considers the rooting depth value of '-1' as not applicable.

**Note 2: Water demand represents the anthropogenic water use and this includes water consumption for dairy farming operations (e.g., cleaning the cowshed). Exotic and native forests require very little to no water, and this is indicated by a minimal water demand volume (0.3 m^3/ha/year).

Table 2. Data sets constructed to run the InVEST Water Yield and Hydropower Valuation model.

Item number	Data set*	Developed using	References
1	Annual average precipitation	NIWA's daily Virtual Climate Network (VCN) Station data	Wratt et al. (2006)
2	Annual average potential evapotranspiration	Same as above	Same as above
3	Depth to root restricting layer	Fundamental Soil Layers (FSL)	LRIS (2010)
4	Plant available water content	Same as above	Same as above
5	Land use/land cover	Land Cover Database v5.0 (LCDB5) layer and Agribase enhanced LCDB	Landcare Research (2020); Assure Quality (2022)
6	Shape file of the sub-catchments	River Environment Classification (REC); Digital Elevation Model (DEM); InVEST DelineateIT model	Snelder, Weatherhead, and Biggs (2004); Columbus, Sirguey, and Tenzer (2011); Sharp, Fisher, and Lacayo (2020)
7	Biophysical table (Plant evapotranspiration coefficient (Kc); Vegetation cover; Rooting depth)	Moderate Resolution Imaging Spectroradiometer (MODIS)	Running et al. (2019)
8	Seasonality constant	Seasonal distribution of precipitation derived from data based on related literature	Donohue, Roderick, and McVicar (2012); Hamel and Guswa (2015)
9	Water demand table	Experts' opinion and related literature	Waikato Regional Council expert; Higham et al. (2017); Journeaux (2020)

* Note: For the details of each data set, please refer to the InVEST manual.

InVEST Hydropower Valuation

The InVEST Hydropower Valuation model was used to evaluate the impact of LULC change on hydropower generation in the study catchment. This model estimates the amount of energy produced based on the estimated water yield, specifications of hydropower stations, and realised water supply in the catchment. Water yield is spatially calculated based on the description above. In terms of data on the hydropower stations, we created an input table in InVEST that includes the average annual effective height of water behind each dam at the turbine intake. Based on interviews with a hydropower dam expert, we assumed that each dam had an efficiency rating of 85% and an expected lifespan of about 70 years. Data used to spatially calculate realised water supply includes the average water demand or water consumption by LULC in Table 1. We used the InVEST Hydropower Valuation model to estimate the change in the volume of water available in the sub-catchment and how that impacted the power generation in gigawatt-hours (GWh).

InVEST Seasonal Water Yield

In applying the InVEST Seasonal Water Yield (SWY) model, we used monthly spatial data to capture the seasonal effects. The data we used for running the SWY model, such as average precipitation, PET, Kc, shape file for sub-catchments, and DEM, were collected from the same sources as the Water Yield model (Table 2). The 15-m cell size resolution DEM was also used for the SWY model. The LULC rasters for the 2001/02 and 2018/19 periods used in the Water Yield model was also used for the SWY model.

In contrast to InVEST Water Yield, the SWY model requires additional data sets such as hydrological soil groups (HSG), a different biophysical table and a rainfall events table. We constructed the HSG data set based on the Fundamental Soil Layer (FSL) and its soil series field and assigning the HSG from S-map online.[3] The final map was converted to a 15-m cell size resolution raster. The biophysical table for SWY was developed by assigning curve numbers to the LULC classes using curve number examples from the USDA Part 630 Hydrology Nation Engineering Handbook, Chapter 9: Hydrologic Soil-Cover Complexes, 2004. The monthly Kc coefficients by LULC class were developed from eight-day averaged Modus[4] 500-m resolution data (MOD16A2GF) for PET, and ET. Data were averaged across each month, and the LULC polygon classes used to capture the PET and ET values for each class. Kc was calculated as the ratio of PET to AET per LULC class. These data were assigned to each LULC class biophysical table.

The rainfall events table was developed using precipitation data where monthly rain day above 0.1mm rainfall were identified and assigned to a .csv table (Wratt et al. 2006). A flow accumulation thresholds value was developed by calculating flow direction and flow accumulation across the 15-m cell size resolution DEM for the study catchment. A series of stream networks was also developed and compared with New Zealand LINZ river vector data[5]; we estimated that somewhere between 500 and 1000 cells contributing toward a stream was normal for the catchment. Therefore, a threshold flow accumulation of 750 cells was assigned to the SWY model.

Quantification of water flow regulation services using InVEST SWY

The SWY module uses the abovementioned spatial data to calculate spatially explicit measures of water flow regulation services in the catchment. These measures include *Quickflow*, *Baseflow* and *Local Recharge*. While SWY accounts for the variation in rainfall and evapotranspiration rates across the different months, the three measures are reported as spatial indices on a per pixel per year basis (Sharp, Fisher, and Lacayo 2020). Spatially explicit outputs from InVEST SWY model were processed using ArcGIS Pro version 2.8 (ESRI 2022) to produce map graphics and calculate key statistics for the full catchment, across the different sub-catchments and across LULC classes.

Water runoff refers to “the movement of water under the influence of gravity in channels of various sizes” (McConchie 2001). Quickflow is water runoff that occurs during or shortly after rain events (Sharp, Fisher, and Lacayo 2020). It is also referred to as “flood flow” (Duncan and Woods 2013). Quickflow is a runoff measure that

[3] https://smap.landcareresearch.co.nz/maps-and-tools/factsheets/
[4] https://modis.gsfc.nasa.gov/about/
[5] https://data.linz.govt.nz/

indicates how the landscape's capacity for rainfall infiltration and flood regulation are changing over time. Quickflow is calculated with a Curve Number (CN)-based approach, which captures soil and land cover properties. Larger CN values have greater runoff potential (e.g. clay soils and low vegetation cover), while lower CN values have lower runoff potential (e.g. sandy soils and dense vegetation cover) (Sharp, Fisher, and Lacayo 2020). Baseflow refers to water reaching streams later when there is no rainfall, e.g. between rain events during the dry season. Local recharge (LR) is the water that becomes available as baseflow that supports dry-season river flows. LR is calculated by subtracting AET plus quickflow from the amount of rainfall (Sharp, Fisher, and Lacayo 2020). The LR index is computed on an annual time scale but uses values derived from monthly water budgets. Quickflow, Baseflow and Local Recharge are influenced by land use change (Fahey et al. 2010; Esse et al. 2021; Bagstad, Ingram, et al. 2020), and in this study, we evaluate the impacts of land use change on each of them in the study catchment. Unlike the InVEST Hydropower Valuation model, where anthropogenic use of water is accounted for in quantifying LULC change impacts on hydropower generation, the SWY model only accounts for climatic and biophysical factors.

Natural Capital Accounting Framework

The concept of natural capital accounting has gained traction globally because of the vital role of natural resources in sustaining economic and human well-being (Bateman and Mace 2020). Most countries have continued to adopt the most widely used measure of a nation's growth and development – the Gross Domestic Product (GDP) – where the contribution of nature to the economy and human well-being is free and limitless. However, while global GDP per capita rose between 1992 and 2014, the value of natural capital per capita has declined significantly (Kumar 2018). Therefore, it is important to show the limits or the "health" of our natural capital. In this study we assess indicators of freshwater resources, which may directly or indirectly affect the economy and society.

Numerous global, national and local initiatives have attempted to value natural capital and ecosystem services to enable their representation in policy and decision making (MEA 2005; UKNEA 2011; Yao et al. 2016). However, these sets of metrics remain in its infancy stage because of the different concepts and understandings of the multiple values provided by ecosystem. This situation contributed to a lack of consistency in the ways these values are analysed or reported. Towards this, the United Nations Statistical Commission endorsed the further development of the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA-EA). SEEA-EA is "an integrated and comprehensive statistical framework for organizing data about habitats and landscapes, measuring ES, tracking changes in ecosystem assets, and linking this information to economic and other human activity" (UN-SEEA 2021).

Natural capital accounts comprise the System of Environmental-Economic Accounts (SEEA) Central Framework and the SEEA Ecosystem Accounts. The Ecosystem Accounting provides a framework to help standardise methods used for valuing and reporting ES data (UN-SEEA 2021). Having a standardised, comprehensive set of values data, through ecosystem accounting, can help improve water management, such as for managing water supply and demand, improving the state of environmental and water resources and adapting to extreme hydro-meteorological events (Vardon et al. 2018).

The Waikato Regional Council commissioned a report that explored a new set of measures that would account for the value of ecosystems and the flow of ES such as recreation, water flow regulation, and water supply provided to society (Gardiner and Huser 2017). Assessing ecosystem services and their values would provide various measures to complement the gross domestic product (GDP), including health and ecosystems limits (Bagstad, Ancona, et al. 2020). The SEEA-EA enables the transformation of traditional economic thinking into a sustainable lens by providing a framework that recognises that our natural resources have limits but can be sustained and enhanced for future generations (UN-SEEA 2021).

This study used spatial modelling approaches to identify the extent of land use change in the study catchment. Using estimated water-related ES values from InVEST, we applied the Zonal Statistics package in ArcGIS PRO (ESRI 2022) to quantify the water flow regulation services by LULC class for the two study years in the catchment. Quantified water ES values by LULC class were used to construct some initial tables that can later be used to start the development of ecosystem accounts (under the water and land themes) for the Waikato region. These accounts are also referred to as "sets of unbiased data for material natural resources, such as forests, energy and water" (WAVES Undated).

Spatial data and outputs from the application of InVEST Water Yield and SWY models can be used to create two ecosystem accounts: Extent Account and the Capacity Account. We developed the extent account here following the proposed extent account in Warnell et al. (2020). It presents the extent of land use change between the two study periods. The Capacity Account provides the capacity of each LULC class to potentially supply water flow regulation services (e.g., water yield, quickflow, local recharge and baseflow) in the study catchment. A capacity account was developed following accounts created by Bagstad, Ingram, et al. (2020) and La Notte, Vallecillo, and Maes (2019).

These two pilot ecosystem accounts can serve as a useful start to develop a complete set of interconnected ecosystem accounts which include physical and monetary accounts as presented in Figure 1. Ideally, this future work should be undertaken by a team consisting of an ecosystem accountants, statisticians, biophysical modellers and ES economists.

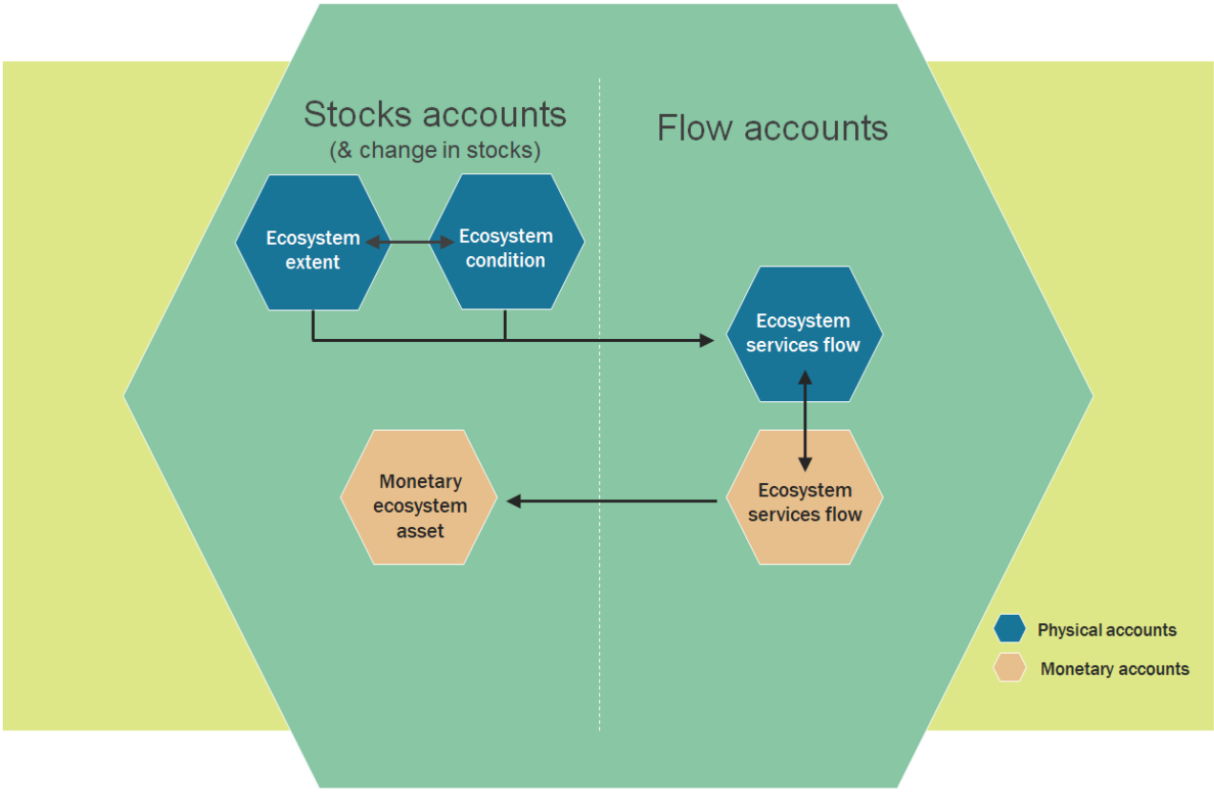


Figure 1. Diagram showing a full set of interconnected ecosystem accounts. (Source: UN-SEEA (2021))

Our Freshwater Ecosystem Services Assessment Framework

Another aim of this study was to develop and apply an assessment framework to quantify land use change impacts on five water availability related ES discussed above. This new framework will consider the variation of the impacts of land use change on the provision of freshwater ES across the different sub-catchments in the study site. This framework will also consider the variation in the provision of freshwater ES across the major LULC classes. The above will be modelled in three different scenarios: (1) impacts of LULC change between the two study years; (2) impacts of LULC change during a high rainfall (wet) year; and (3) impacts of LULC change during a low rainfall (dry) year.

Study Site and Land Use Data

The Waikato Region is New Zealand's fourth-largest region with a total land area of 2.5 million hectares (Waikato Regional Council undated). In 2018, the region had a population of 458,202, accounting for 10% of New Zealanders. It has a wide variety of natural assets, including freshwater resources, that serve as foundation for economic growth while also contributing to human well-being. In terms of freshwater resources, it has at least 100 lakes, 20 rivers and 1,420 streams. These waterbodies include the nation's largest lake (Lake Taupō) and longest river (Waikato River).

Our freshwater ES assessment focuses on a river catchment that starts from Tūrangi in the south to Ngāruwāhia in the northwest (Figure 2). Lake Taupō is the large lake near the southern section of the study catchment. The study catchment has an area of 838,505 hectares accounting for about one-third of the region. In 2001, planted forests (247,605 ha) accounted for the largest proportion of the land use (29.5%), followed by sheep, beef and cattle farming (22.7%), indigenous forest (12.3%) and dairying (11.6%).

Based on the maps for the two time periods, 2001/02 and 2018/19, the catchment lost about 45,757ha of exotic planted forests and 27,570ha of sheep, beef and cattle farms. This corresponded with an increase in area for dairying by about 81,668ha (Table 3). This is an 84% increase in the dairy farming area while exotic forests and sheep, beef and cattle farming decreased by 18% and 14%, respectively.

The extent of land use change to dairying is illustrated in Figure 3, where some of the existing planted forests (in green) in 2001/02 were converted to dairying (in bright blue) in 2018/19. A few patches of deer farming (in pink) in 2001 were mostly converted to dairying in 2018/19. The change in the distribution of key land uses between the two time periods is illustrated in Figure 4 where the proportion of dairying increased from 12% in 2001/02 to 21% in 2018/19, while the proportion of exotic forests and sheep, beef and cattle farming decreased by 6% and 4%, respectively.

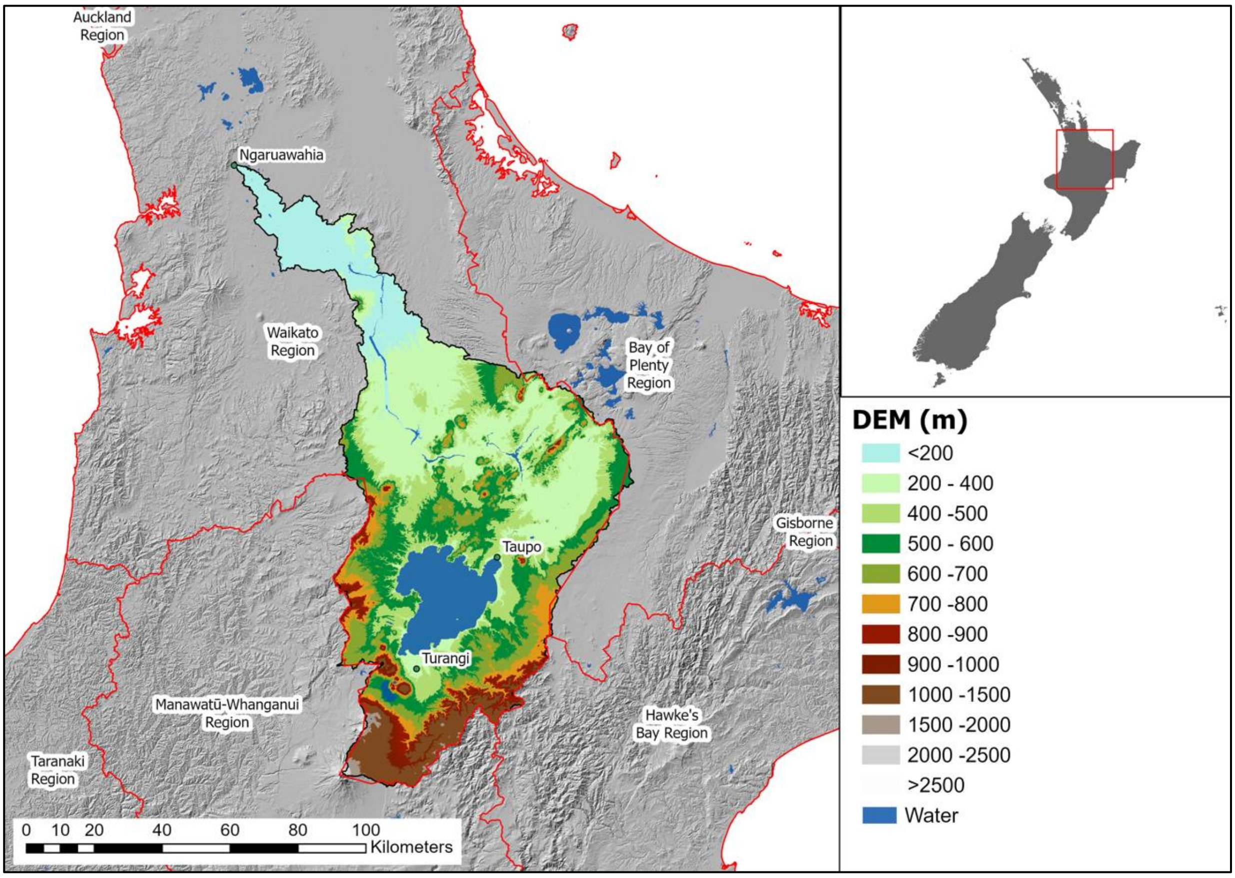


Figure 2. Map showing the location of the catchment study site.

Table 3. Land use/land cover (LULC) distribution in 2001/02 and 2018/19 in the study catchment.

Land use	Area in 2001/02 (ha)	Area in 2018/19 (ha)	Change in area (ha)	% Change in area
Exotic forests	247,605	201,848	-45,757	-18.5
Sheep, beef and cattle farming	190,037	162,466	-27,570	-14.5
Indigenous forest	103,283	101,559	-1,724	-1.7
Dairying	97,538	179,207	81,668	83.7
Water	69,236	69,199	-37	-0.1
Shrublands	34,410	33,825	-585	-1.7
Broadleaved indigenous hardwoods	29,829	29,361	-468	-1.6
Dairy dry stock	14,575	15,580	1,006	6.9
Deer farming	11,914	3,639	-8,275	-69.5
Built-up areas	11,670	13,589	1,919	16.4
Herbfield and tussock grasslands	11,642	11,642	0	0
Permanent snow and ice	7,794	7,787	-6	-0.1
Wetlands	3,072	2,767	-305	-9.9
Deciduous hardwoods	2,042	1,745	-297	-14.5
Short-rotation cropping	1,953	1,922	-31	-1.6
Fruit orchards and vineyards	682	848	166	24.3
Sand, gravel, rocks	664	615	-49	-7.4
Vegetable and flower production	456	801	345	75.6
Transport infrastructure	103	103	0	0
TOTAL	**838,505**	**838,505**		

Note: Land use data created using LCDB v. 5 and Agribase Enhanced LCDB

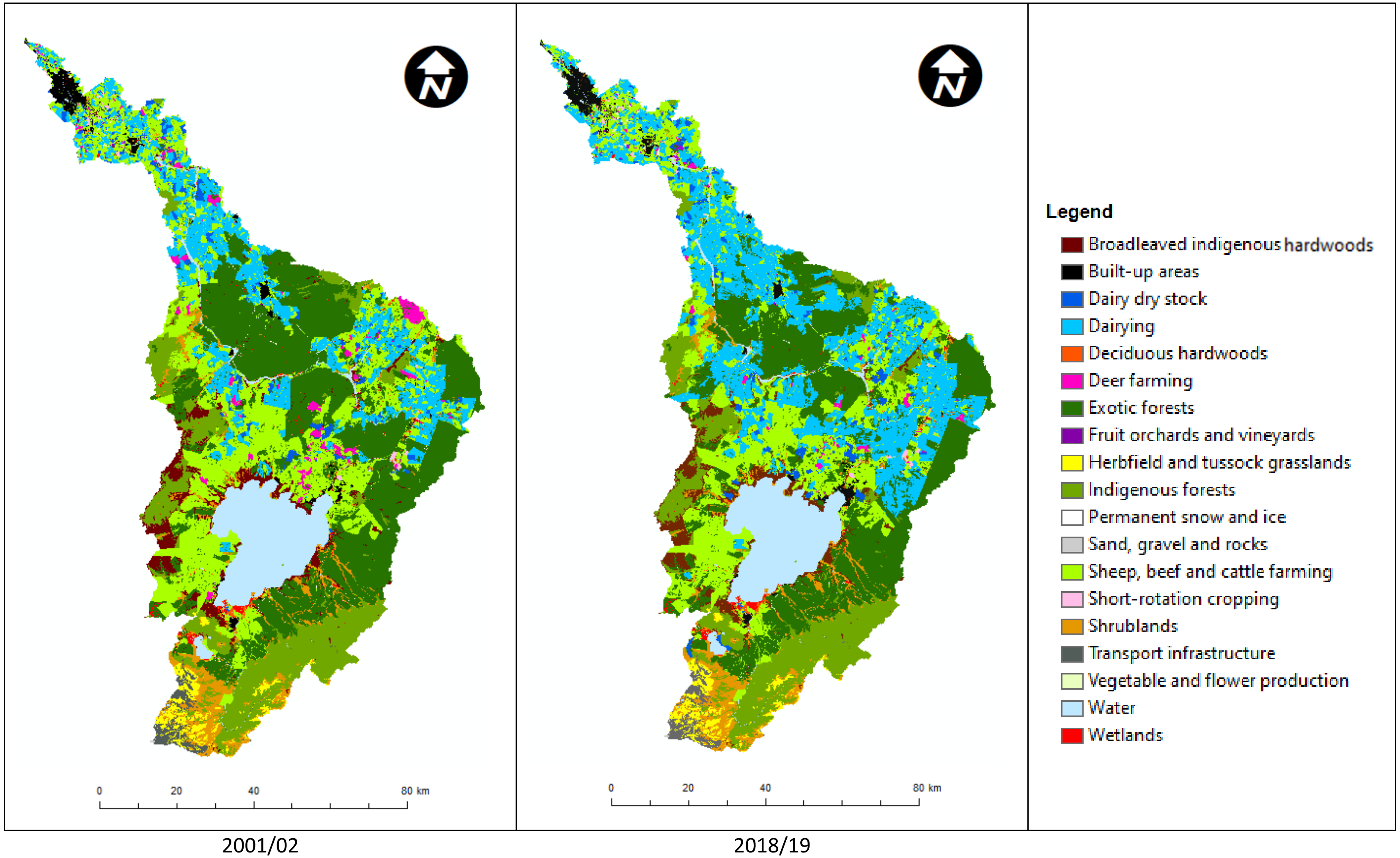
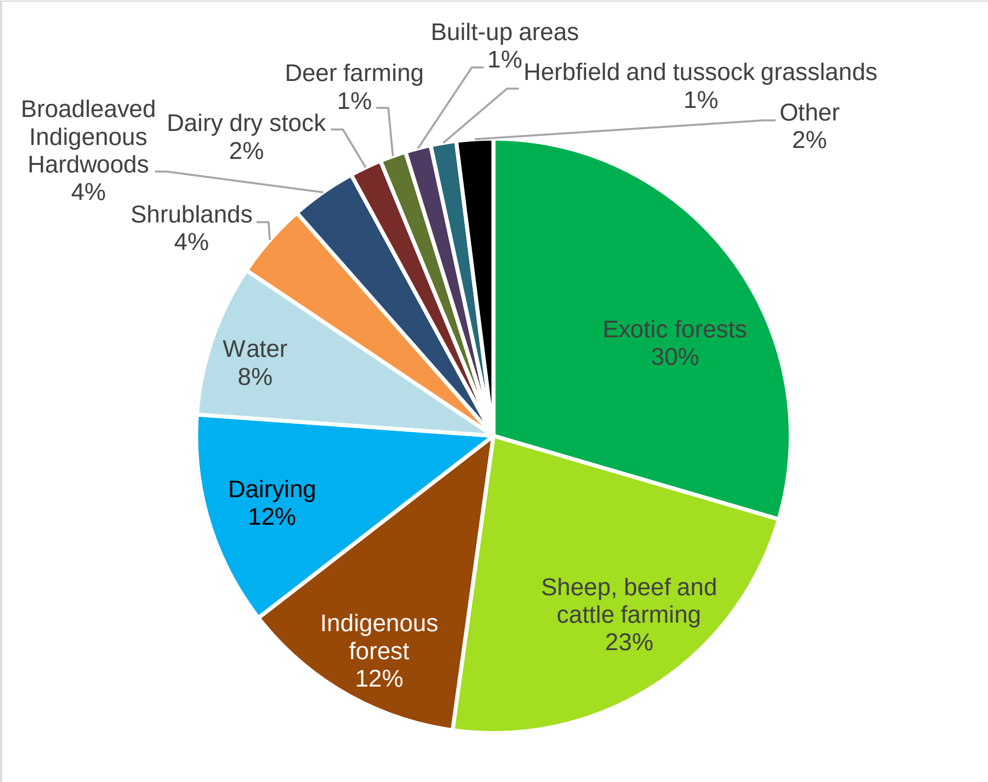
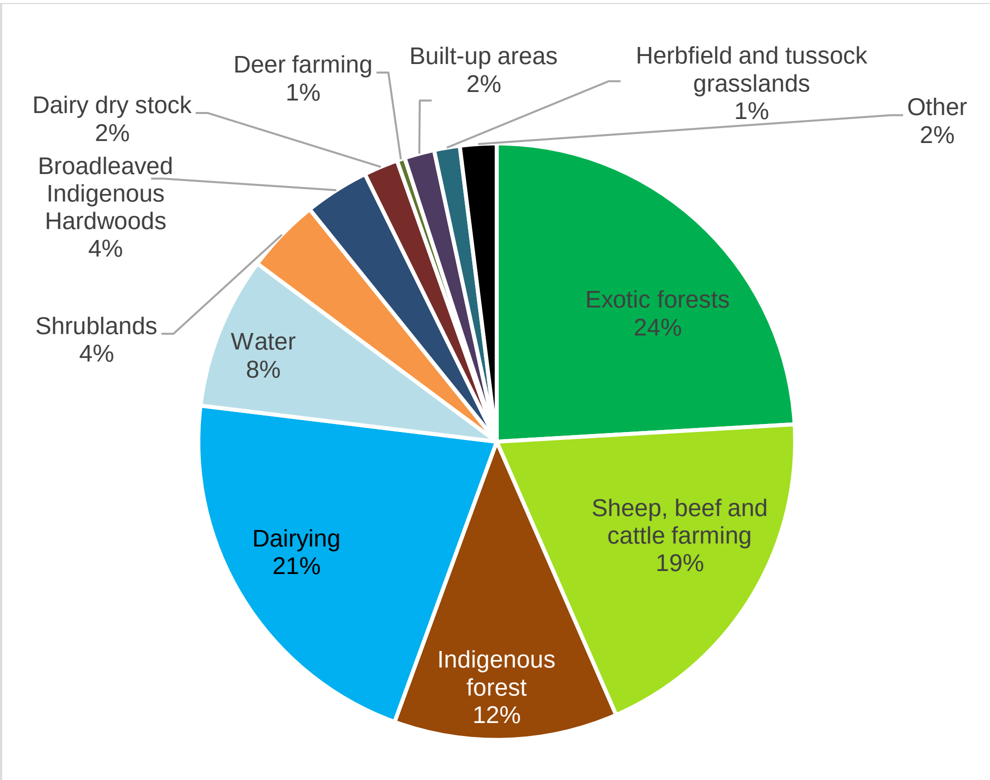


Figure 3. Spatial land use / land cover distribution in 2001/02 and 2018/19 in the study site.



2001/02



2018/19

Figure 4. Statistical LULC distribution (%) in 2001/02 and 2018/19 in the catchment study site.

As mentioned in the methods section, we used the InVEST DelineateIT module to identify the eight different (but not mutually exclusive) sub-catchments within the full study catchment. The sub-catchments were identified based on the location of the eight hydropower stations all sourcing their water mainly from the Waikato River (Figure 5). We present in Appendices A1 and A2 the eight sub-catchments, each with a map of the distribution of LULC classes, over the two time periods.

Aratiatia is the smallest sub-catchment with an area of 357,000 hectares, accounting for 42% of the full catchment (Table 4). Amongst the hydropower stations, Aratiatia has the third lowest average power generation (331 GwH) and is located closest to Lake Taupō (Table 5, Figure 5). Karapiro is the largest sub-catchment which contains the hydropower dam with the second highest average power generation of 490 GwH (Table 5). Maraetai has two sets of hydropower dams (i.e., Maraetai 1 and 2), but it is classified as a single hydropower station with a total usual power generation of 856 GwH (Table 5). The eight hydropower stations act to form the "Waikato River hydro lakes”[6] along the Waikato River. The hydropower stations, on average, have a combined production capacity of more than 4,000 GwH per year which account for about 13% of the total electricity supply of New Zealand (NIWA Project Team 2010).

[6] https://www.waikatoregion.govt.nz/environment/natural-resources/water/lakes/where-are-our-lakes/

Figure 5. Map of the catchment study site showing the location of the eight hydropower stations.

We present in Table 4 the percentage change in the area by LULC class by sub-catchment.
We focus on the top four LULC classes which account for more than 76% of the catchment's total area in the two time periods. Amongst the eight sub-catchments, only Aratiatia increased exotic forest area by 9% (~5,983 ha), while the other sub-catchments decreased exotic forest area by at least 12%, with Karapiro having the greatest area reduction of 18.5%. For the sheep, beef and cattle farming, all sub-catchments decreased in area between 13% and 18%, with Aratiatia having the least decline. All sub-catchments expanded their dairying areas, with Aratiatia having the least expansion of 83.1% (~1,518 ha) while Whakamaru increased the most with 121.8% (~47,023 ha) (Table 4). This percentage change in land area for dairy may mask the actual area expansion relative to other sub-catchments, so we also looked at the proportion of dairying for each sub-catchment in both periods. In 2001/02, dairying in Aratiatia accounted for only 0.5% of the sub-catchment, increasing to 0.9% in 2018/19 (Appendix B). The rest of the sub-catchments had at least 5.7% of their respective areas in dairying in 2001/02 (Ohakuri). Karapiro's proportion of dairying was 10.6% in 2001/02, and it increased to 20.6% in 2018/19.

Table 4. Percentage change in area by land use/land cover in 2001/02 and 2018/19 by sub-catchment and the full catchment.

Land use / Land cover	Percentage (%) change in area								
	Aratiatia	Ohakuri	Ātiamuri	Whakamaru	Maraetai	Waipapa	Arapuni	Karapiro	Full catchment
Exotic forests	8.6	-12.1	-13.0	-14.1	-15.2	-14.8	-15.0	-18.5	-18.5
Sheep, beef and cattle farming	-13.3	-15.0	-15.8	-14.4	-14.4	-15.1	-15.8	-15.4	-14.5
Indigenous forest	-0.5	-1.0	-0.9	-1.0	-1.4	-1.4	-1.4	-1.5	-1.7
Dairying	83.1	116.0	113.7	121.8	118.8	119.9	116.4	95.1	83.7
Water	0.0	-0.0	-0.0	-0.0	-0.1	-0.1	-0.0	-0.0	-0.1
Shrublands	-0.8	-0.6	-1.1	-1.2	-2.2	-1.2	-1.3	-1.4	-1.7
Broadleaved indigenous Hardwoods	0.2	-0.8	-1.1	-1.2	-1.0	-1.2	-1.3	-1.5	-1.6
Dairy dry stock	270.2	74.6	71.5	46.5	40.7	40.8	40.2	23.6	6.9
Deer farming	-78.0	-69.1	-70.3	-71.3	-70.5	-70.5	-70.3	-70.0	-69.5
Built-up areas	51.0	48.0	47.8	47.3	41.4	41.4	41.3	25.2	16.4
Herbfield and tussock grasslands	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Permanent snow and ice	0.3	0.3	0.3	0.4	0.2	0.2	0.2	0.0	-0.1
Wetlands	1.0	-1.2	-3.6	-8.3	-8.4	-8.7	-8.7	-9.8	9.9
Deciduous hardwoods	3.8	-4.3	-11.0	-12.2	-13.7	-14.6	-14.6	-14.2	-14.5
Short-rotation cropping	2.9	4.1	4.1	4.0	4.1	4.1	0.4	3.0	-1.6
Fruit orchards and vineyards	270.6	838.4	838.4	825.0	838.4	838.4	838.4	34.9	24.3
Sand, gravel, rocks	-7.1	-12.6	-12.4	-12.7	-14.2	-12.1	-12.1	-14.6	-7.4
Vegetable and flower production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-44.2	75.6
Transport infrastructure	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total area (hectares)	***356,648***	***505,533***	***533,309***	***584,375***	***649,545***	***675,176***	***700,636***	***781,115***	***838,505****
% of the full catchment	***42.5***	***60.3***	***63.6***	***69.7***	***77.5***	***80.5***	***83.6***	***93.2***	***100.0***

* Note: We study here eight overlapping sub-catchments as shown in Appendices A1 and A2. Therefore, the total area of the full catchment is not the summation of the area of the eight sub-catchments. There are also some areas in the full catchment that are not included in any of the eight sub-catchments.

Table 5. The nine hydropower generation dams with approximated actual energy generation.

Item number	Hydropower dam	Average annual energy generation (GWh)*	Proportion (%) from total annual energy generation	Approximated actual energy generation in 2001/02 (GWh)	Approximated actual energy generation in 2018/19 (GWh)
1	Aratiatia	331	8.3	310	213
2	Ohakuri	400	10.0	375	257
3	Ātiamuri	305	7.6	286	196
4	Whakamaru	486	12.1	455	312
5	Maraetai 1	428	10.7	401	275
6	Mareaitai 2	428	10.7	401	275
7	Waipapa	330	8.2	309	212
8	Arapuni	805	20.1	754	517
9	Karapiro	490	12.2	459	315
	TOTAL	**4,002**	**100.0**	**3,750****	**2,571*****

* Data based on Mighty River Power's website (accessed on 9 March 2022) - https://web.archive.org/web/20060806174438/http://www.mightyriverpower.co.nz/Generation/AboutUs/HydroStations/Default.aspx
** Actual energy generation reported in Mighty River Power (2002)
*** Actual energy generation reported in Mercury (2019)

Results

We present the results from the InVEST Water Yield and Seasonal Water Yield models and the pilot ecosystem accounts that can be used for the construction of fully interconnected ecosystem accounts for freshwater related ES in the region.

InVEST Water Yield and Hydropower Generation

Results from the InVEST Water Yield model indicate that the amount of rainfall in the full catchment was 24% less in 2018/19 (1,139 mm) compared with 2001/02 (1,497 mm) (Table 6). Consequently, estimates for annual water yield show that the full catchment had a 39% reduction in water yield from 845 million m^3 in 2001/02 to 513 million m^3 in 2018/19. Water yield reduction volume is illustrated by the lighter blue colour in the 2018/19 map in Figure 6.

To check if the water yield estimates for the study site are robust, we compared our results with the 2018 water yield spatial data generated by New Zealand's WATYIELD water balance model (Fahey et al. 2010). WATYIELD water yield estimates for 2018 is juxtaposed with the InVEST results for 2018/19 in Appendix C. Although there are some variations across the two maps, the volume of water for the whole study catchment was about 633 million m^3 from WATYIELD, which lies in between our InVEST water yield estimates of 513 million m^3/year and 845 million m^3/year. Therefore, the InVEST water yield estimates are comparable to the estimates from WATYIELD.[7]

The InVEST water consumption model component shows that there had been an increase of 47% in the water consumption across the catchment between the two time periods. One reason for this increase is that dairying uses more water (116 m^3/ha/yr) compared with exotic forestry (0.3 m^3/ha/yr) and deer farming (37.1 m^3/ha/yr). In contrast to other sub-catchments, which had a substantial area that was converted from forestry to dairying, Aratiatia had a relatively smaller expansion area of dairying (1,518 ha), while forestry area increased by a greater magnitude (5,983 ha). This contributed to only a 4% increase in water consumption in Aratiatia compared to at least 53% increase in other sub-catchments.

[7] The InVEST Water Yield modelling platform can be access by everyone while the WATYIELD modelling platform requires permission prior to its use.

Considering the reduction in water yield and increased water consumption due to land use change between the two study periods, we found a reduction in hydropower energy production in the nine hydropower stations from 41% in Aratiatia to 52% in Karapiro (Table 6). This significant reduction in hydropower generation can be attributed to the combined effects of the difference in the climatic condition and land use change to more intensive productive use. We find a greater hydropower reduction in the modelling results than the reported actual hydropower reduction in the catchment. Based on annual reports of Mercury Energy (formerly Mighty River Power), the actual overall power generated by the hydropower stations in 2001/02 was about 3,750 GWh, and this was reduced by about 31% to 2,571 GWh in 2018/19 (Mercury 2019; Mighty River Power 2002). There could be other factors that might have contributed to lower power generation in addition to the amount of rainfall, volume of water consumed by each type of land use and land use change. A large volume of water that flows through the Waikato river comes from Lake Taupō, and this might have mitigated the impacts of having less rainfall in 2018/19.

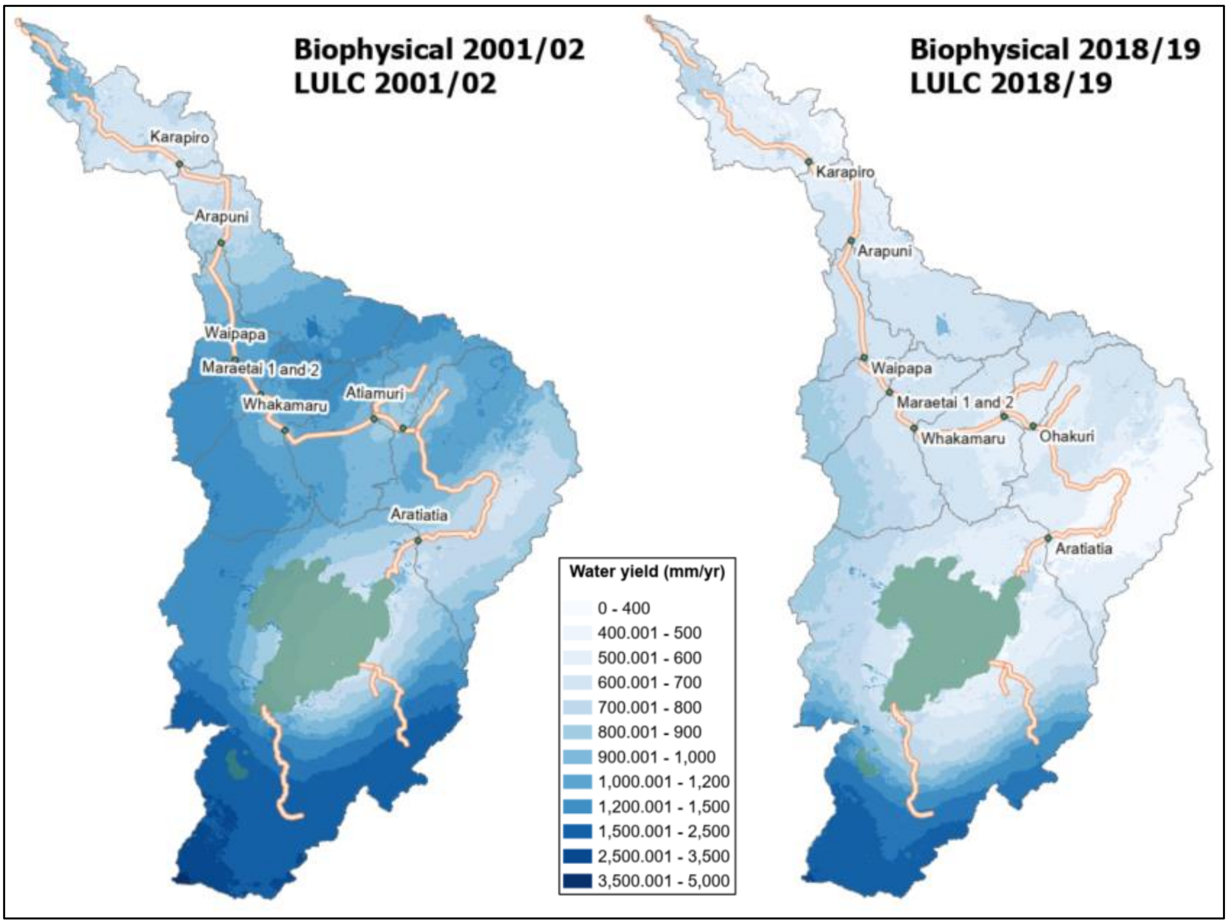


Figure 6. InVEST modelled water yields (mm/year) in the Waikato River Catchment 2001/02 and 2018/19.

Table 6. Percentage change in rainfall, annual water yield, water consumption and hydropower generation over the two time periods.

Sub-catchment	Area (ha)	Percentage (%) change in mean				
		Annual rainfall	Actual evapo-transpiration	Annual water yield	Volume of water consumed	Hydropower generation
Aratiatia	356,648	-25.2	10.7	-39.2	4.0	-40.7
Ohakuri	505,533	-24.9	9.8	-40.2	52.8	-47.5
Ātiamuri	533,309	-24.9	9.7	-40.3	54.2	-48.4
Whakamaru	584,375	-24.9	9.6	-40.5	58.3	-49.3
Maraetai 1 and 2	649,545	-25.0	9.4	-40.5	59.0	-50.1
Waipapa	675,176	-24.9	9.3	-40.4	58.8	-49.8
Arapuni	700,636	-24.8	9.1	-40.3	58.1	-50.2
Karapiro	781,115	-24.4	8.6	-39.9	54.5	-52.0
Full catchment	**838,505**	**-23.9**	**7.9**	**-39.3**	**47.2**	

As stated earlier, the amount of rainfall was substantially higher in 2001/02 (1,497mm) compared with 2018/19 (1,139mm), while the average annual rainfall in the most populated area in the region (Hamilton) was about 1,254mm.[8] We, therefore, refer to 2001/02 as the *wet year* while 2018/19 as the *dry year*.

It is difficult to directly assess the influence of land use change on water yield when the climatic differences between the wet and dry years are so strong. For this reason, we undertook two additional sets of Water Yield model runs: in the first set we used the 2001/02 rainfall and other biophysical data and ran those with LULC 2001/02 and then LULC 2018/19 (Figure 7); in the second set we used the 2018/19 biophysical and rainfall data with LULC for 2001/02 and 2018/19 (Figure 8).

Results from the 2001/02 runs in Figure 7 show slightly lighter blue shades in 2018/19 compared with 2001/02, particularly in the southeastern section of the catchment (circled in red). This indicates a slight reduction (or minimal difference) in water yield due to land use change. We present in Table 7 the overall percentage decrease in water yield during the wet year 2001/02 by sub-catchment where Aratiatia had the least reduction of 0.01% while Karapiro had the greatest reduction of 0.31%. During the dry year of 2018/19, there was a more consistent reduction in water yield between 0.06% and 0.08% across the sub-catchments. This pattern is also illustrated in Figure 8, with slight changes in the intensity of the blue shade between the two time periods. The above results are consistent with the findings from an InVEST Water Yield application by Wei et al. (2021), which shows that a shift to a more intensive land use reduces water yield.

We also report in Table 7 the percentage change in water consumption by sub-catchment. Percentage changes are expected to be the same for each sub-catchment for wet and dry years. This is because LULC change that occurred between 2001/02 and 2018/19 is the same for both years. Water consumption was calculated based on the water demand of both productive (e.g., dairy farms, sheep and beef farms, exotic forestry) and conservation areas (e.g., indigenous forests) shown in the last column of Table 1.

[8] http--s://en.climate-data.org/oceania/new-zealand/waikato/hamilton-1075/

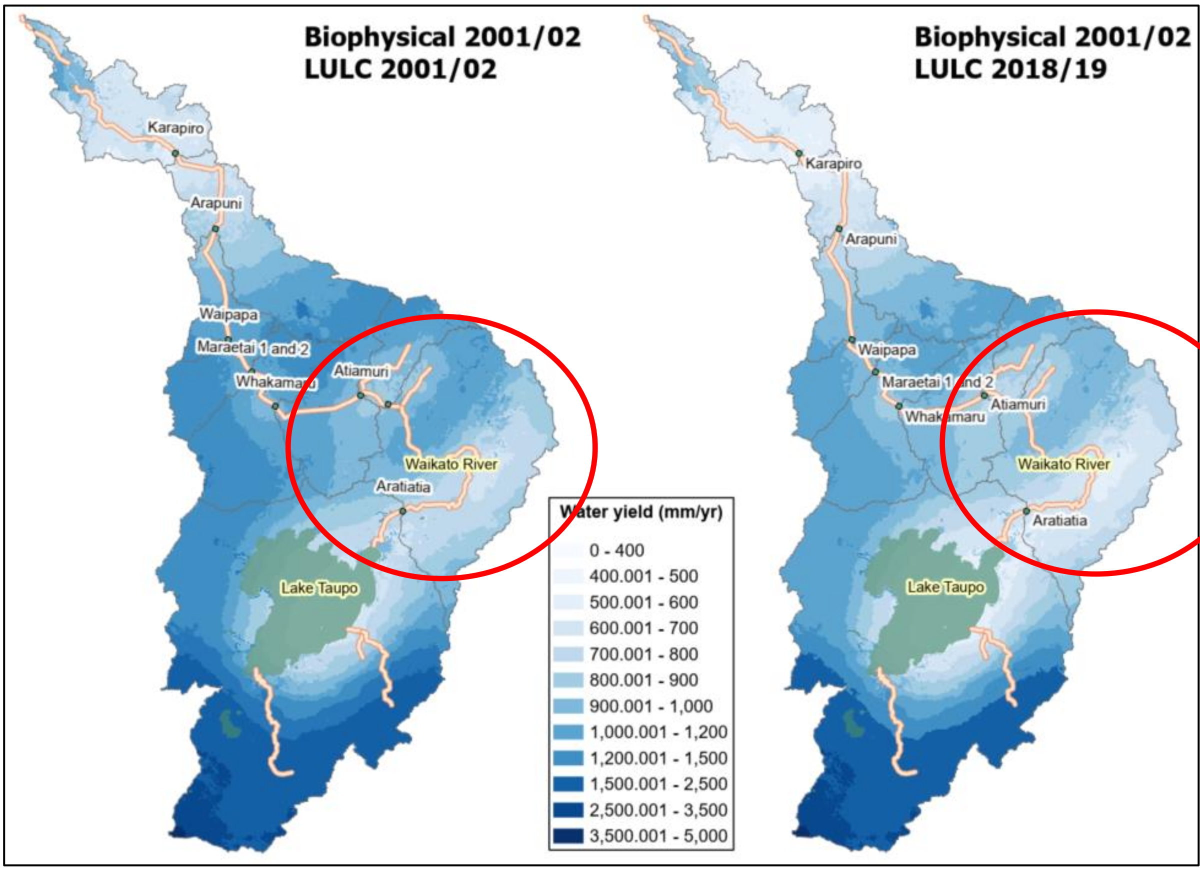


Figure 7. InVEST modelled water yields (mm/year) in the Waikato River Catchment using biophysical and rainfall data in 2001/02 with LULC classes for 2001/02 and 2018/19.

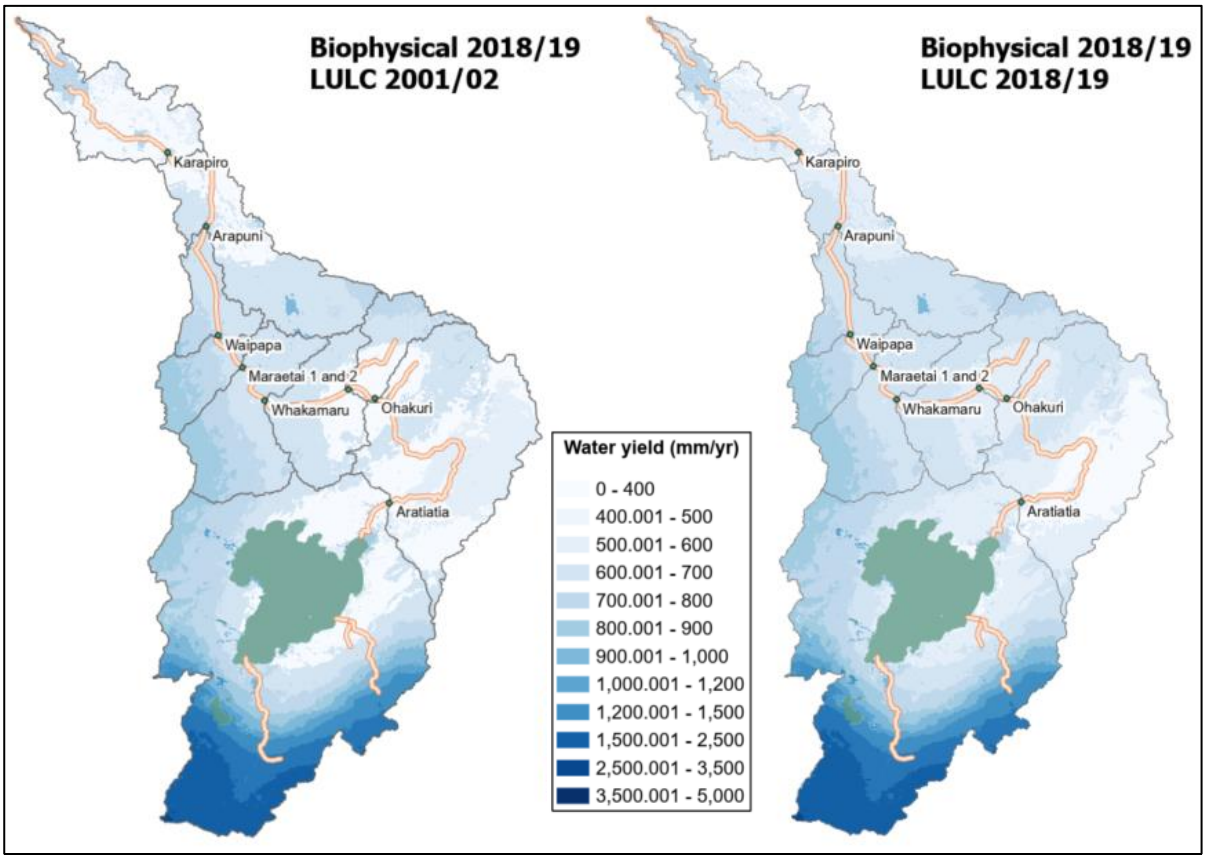


Figure 8. InVEST modelled water yields (mm/year) in the Waikato River Catchment using biophysical and rainfall data in 2018/19 with LULC classes for 2001/02 and 2018/19.

Table 7. Percentage change in water yield, water consumption and hydropower generation for each study year while controlling for the change in LULC.

Sub-catchment	Area (ha)	Water Yield		Water consumption (residence & land use)[9]		Hydropower generation	
		2001/02	*2018/19*	*2001/02*	*2018/19*	*2001/02*	*2018/19*
Aratiatia	356,648	-0.01%	-0.08%	26.7%	26.7%	-1.9%	-3.3%
Ohakuri	505,533	-0.08%	-0.07%	44.8%	44.8%	-4.7%	-8.3%
Ātiamuri	533,309	-0.09%	-0.07%	45.7%	45.7%	-5.0%	-8.8%
Whakamaru	584,375	-0.10%	-0.06%	48.2%	48.2%	-5.3%	-9.4%
Maraetai 1 & 2	649,545	-0.11%	-0.06%	47.4%	47.4%	-5.4%	-9.7%
Waipapa	675,176	-0.11%	-0.07%	47.2%	47.2%	-5.3%	-9.5%
Arapuni	700,636	-0.11%	-0.07%	46.9%	46.9%	-5.5%	-9.8%
Karapiro	781,115	-0.13%	-0.06%	41.5%	41.5%	-6.1%	-11.1%
Full catchment	**838,505**	**-0.09%**	**-0.01%**	**29.6%**	**29.6%**		

In terms of water consumption, the results indicate a substantial increase in consumption in all sub-catchments due to changes in LULC. The smallest increase of 27% was in Aratiatia (smallest sub-catchment) where the area for dairying increased by 83%, while the area of forestry increased by 9%. The largest increase in water consumption was in the sub-catchments of Whakamaru (48%), Maraetai (47%) and Waipapa (47%), where the area of dairying had increased by 122%, 119% and 120% respectively, while the area of forestry had reduced by 14%, 15% and 15%, respectively (Table 4).

For hydropower generation, the results suggest a reduction in hydropower generation for all sub-catchments in both wet and dry years due to land use change.[10] As a percentage of the sub-catchment areas, the reduction rates for all sub-catchments were greater during the dry year. The Aratiatia sub-catchment had consistently experienced the smallest reduction in hydropower generation for both wet (2%) and dry (3%) years while the Karapiro sub-catchment consistently had the greatest reduction in hydropower generation for both wet (6%) and dry (11%) years. These results are consistent with the findings of other studies that applied the InVEST module, which also showed reductions in hydropower generation following a shift to more intensive land use (Aneseyee et al. 2022).

InVEST Seasonal Water Yield

Using the InVEST Seasonal Water Yield (SWY) model, we evaluated the impacts of land use change on the baseflow, quickflow and local recharge. With 2018/19 having 24% less rainfall in the full catchment, annual quickflow decreased by about 26% (Table 8). We illustrate the annual quickflow for the two study years in Figure 9. In Table 8 while there is a consistent 26% reduction in the mean quickflow across all the sub-catchments, Aratiatia had the greatest reduction in median (50th percentile) quickflow.

[9]These two columns are expected to be the same as LULC change is the same for both years. Water consumption is based on the water demand of both productive (e.g., dairy farms, sheep and beef farms, exotic forestry) and conservation (e.g., indigenous forests) areas.

[10] The magnitude of reductions in hydropower generation is much less in this modelling scenario because we are only accounting for the impacts of land use change and not climatic difference, unlike in the earlier Water Yield modelling results where we have accounted for both.

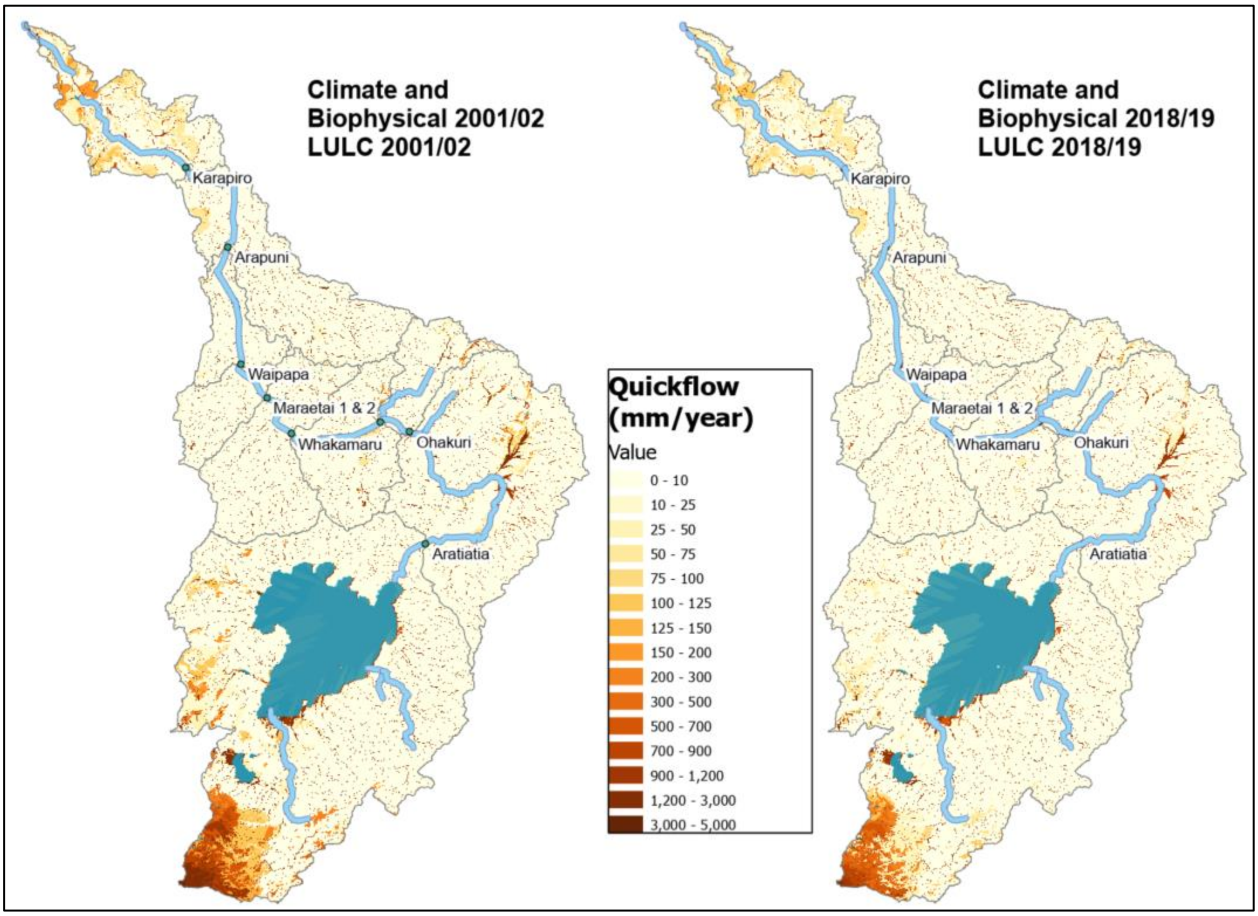


Figure 9. InVEST SWY modelled Quick Flow (mm/yr) in 2001/02 and 2018/19.

Table 8. Percentage change in quickflow, local recharge and baseflow between the two time periods 2001/02 and 2018/19.

Sub-catchment	Area (ha)	QuickFlow		Local recharge		BaseFlow	
		Mean	Median	Mean	Median	Mean	Median
Aratiatia	356,648	-26.3	-91.5	-38.5	-40.0	-37.7	-40.1
Ohakuri	505,533	-26.3	-91.9	-40.9	-43.5	-39.8	-43.5
Ātiamuri	533,309	-26.4	-91.2	-41.1	-43.7	-40.0	-43.7
Whakamaru	584,375	-26.5	-92.1	-41.6	-44.1	-40.4	-44.1
Maraetai 1 & 2	649,545	-26.5	-92.6	-41.7	-43.9	-40.5	-44.0
Waipapa	675,176	-26.5	-92.7	-41.5	-43.7	-40.4	-43.7
Arapuni	700,636	-26.5	-92.0	-41.5	-43.3	-40.4	-43.3
Karapiro	781,115	-26.2	-84.0	-41.4	-43.4	-40.2	-43.4
Full catchment	*838,505*	-25.9	-81.4	-40.9	-43.3	-39.7	-43.3

Local recharge on average decreased by about 41% across the full catchment between 2001/02 and 2018/19 (Table 8). This is illustrated in Figure 10 where the catchment map in 2018/19 has increased in areas shaded in yellow and orange than 2001/02. Aratiatia had the lowest mean (38.5%) and median (40.0%) percentage reduction in local recharge compared with the other sub-catchments (Table 8). Estimates of baseflow exhibit similar patterns as local recharge, whereas the Aratiatia sub-catchment had the smallest reduction in both median and mean baseflow (Figure 11 and Table 8). Results for both local recharge and baseflow imply that the sub-catchment with the least conversion to a more intensive land use had the least reduction in hydrological support for dry-season river flows.

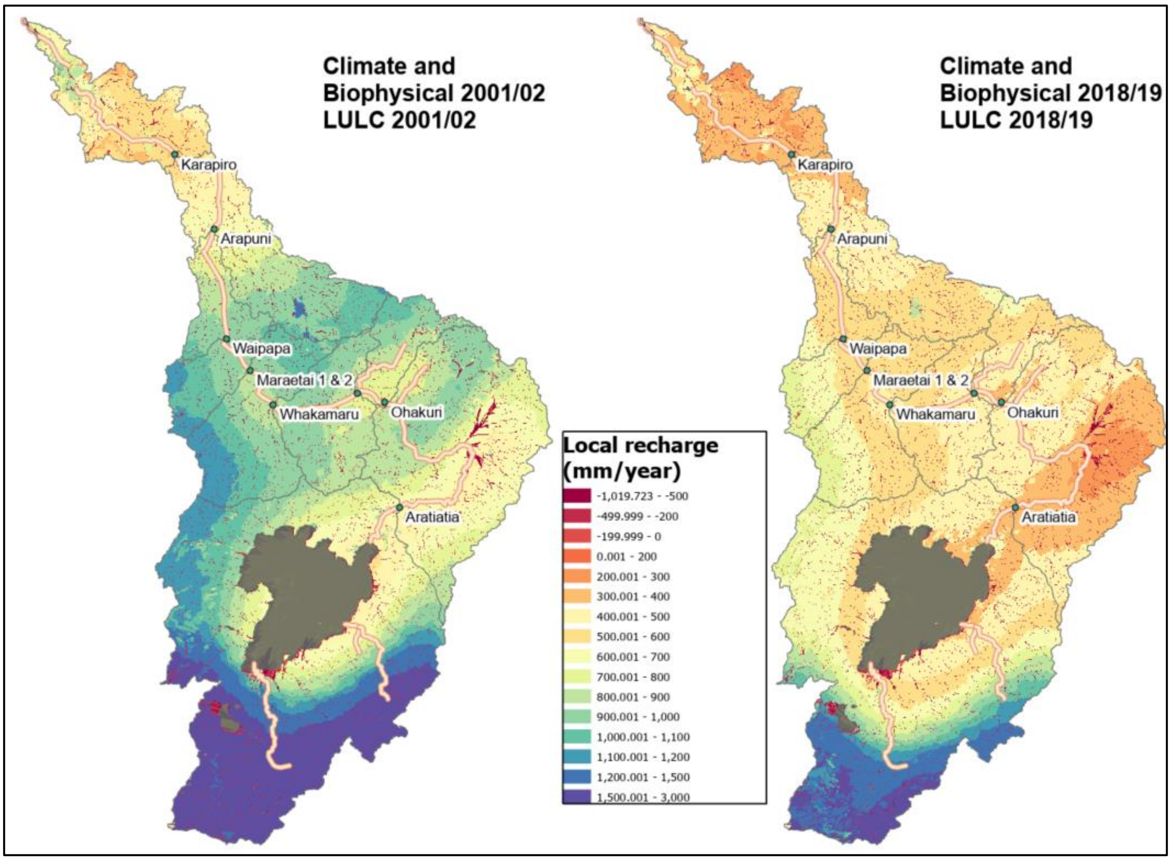


Figure 10. InVEST Seasonal Water Yield modelled Local Recharge (mm/yr) in 2001/02 and 2018/19.

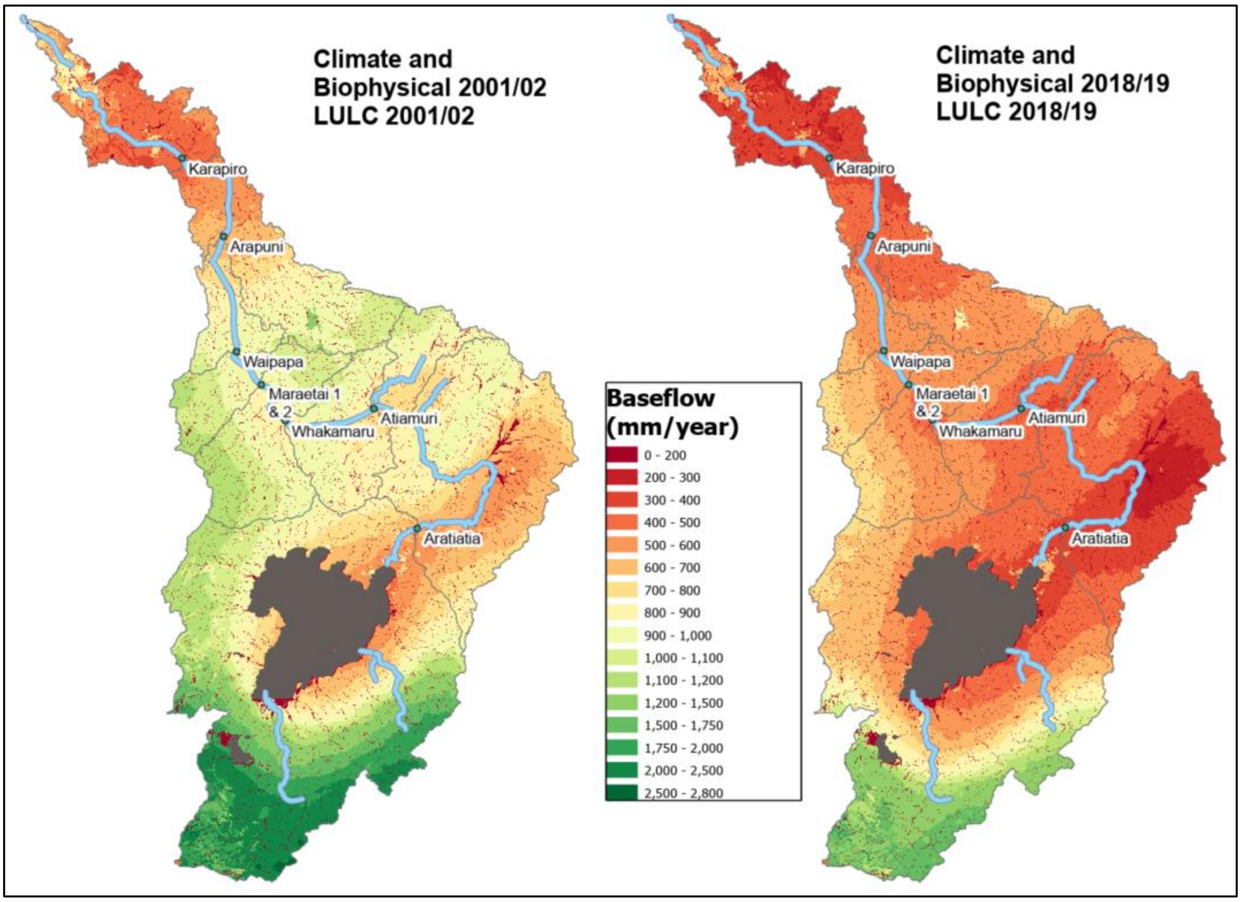


Figure 11. InVEST Seasonal Water Yield modelled Baseflow (mm/yr) in 2001/02 and 2018/19.

Similar to the spatial modelling for water yield, we also employed two additional sets of model runs for SWY, the first for 2001/02 and the second for 2018/19. For each set, we used the same monthly biophysical and rainfall data set while allowing LULC to vary. Estimates of quickflow under this modelling scenario suggest a mixture of results for the two time periods. A reduction in quickflow was estimated for all sub-catchments during the wet year. In the dry year, only Aratiatia had a slight increase in quickflow (+0.01%) while the rest had a reduction. The low change in quickflow for Aratiatia may be associated with this sub-catchment also having the lowest extent of land use change. In addition, the percentage change in the coefficient of variation (the standard deviation divided by the mean) of quickflow is lowest in Aratiatia compared with the other sub-catchments. This predicts that Aratiatia also has the least variability in quickflow, a key indicator for rivers and streams to support the establishment of algae, macro-invertebrates and thereby fish.[11]

Our results suggest relatively minor impacts of land use change on baseflow and local recharge indices (Table 9). However, the Aratiatia sub-catchment is unique compared with other sub-catchments as it is the only sub-catchment that experienced an increase in baseflow and local recharge in both wet and dry years. This indicates that the rivers and streams in this sub-catchment would be likely to have a slightly greater flow of freshwater during the dry months, indicating a more stable water flow regime across seasons. This can help support aquatic life as well as providing for agricultural and residential needs in the region (Duncan and Woods 2013). The above results are consistent with those in Ahiablame et al. (2017) which indicated that a 1% increase in agricultural land use resulted to a 0.2% decrease in baseflow.

[11] Clausen and Biggs (1997) show that rivers and streams with lower quicklflow variability provide better ecological support for the establishment of algae and macro-invertebrates.

Table 9. Percentage change in quickflow, local recharge and baseflow with land use change by sub-catchment over the two time periods.

Sub-catchment	**Area (ha)**	**Quickflow**		**Local recharge**		Baseflow	
		2001/02	*2018/19*	*2001/02*	*2018/19*	*2001/02*	*2018/19*
Aratiatia	356,648	-0.03	0.01	0.09	0.07	0.09	0.08
Ohakuri	505,533	-0.10	-0.05	-0.11	-0.12	-0.09	-0.10
Ātiamuri	533,309	-0.16	-0.10	-0.11	-0.12	-0.10	-0.12
Whakamaru	584,375	-0.23	-0.16	-0.12	-0.12	-0.12	-0.13
Maraetai 1 & 2	649,545	-0.25	-0.18	-0.14	-0.15	-0.14	-0.16
Waipapa	675,176	-0.26	-0.19	-0.14	-0.14	-0.14	-0.16
Arapuni	700,636	-0.26	-0.19	-0.15	-0.16	-0.15	-0.17
Karapiro	781,115	-0.29	-0.22	-0.20	-0.21	-0.20	-0.21
Full catchment	**838,505**	**-0.30**	**-0.24**	**-0.15**	**-0.14**	**-0.15**	**-0.15**

Ecosystem accounting

We constructed the pilot ecosystem extent account following Warnell et al. (2020) (Appendix D). The LULC classes have been colour coded consistently with the map in Figure 3. The ecosystem extent account presents the changes in the 19 LULC classes between 2001/02 and 2018/19. The most prominent changes during this time are the gains in the area of dairying (+81,664 ha), built-up areas (+1,920 ha) and dairy dry stock (+1,003 ha); and declines in exotic forests (-45,757 ha), sheep, beef and cattle farming (-27,563 ha) and deer farming (-8,274 ha).

We also constructed the pilot capacity account tables that show the capacity of each LULC class to potentially supply four water flow regulation services (water yield, quickflow, local recharge and baseflow) in the study catchment. This account was developed following Bagstad, Ingram, et al. (2020) and La Notte, Vallecillo, and Maes (2019). The capacity account is presented in three tables. The first table provides the supply of water flow regulation services between 2001/02 and 2018/19, thereby accounting for the impacts of LULC change between the two study years (Appendix E1). The second and third tables focused on presenting the impacts of LULC change for the wet and dry years (Appendices E2 and E3).

We present in Appendix E1 the capacity account where we consider the change in climatic factors and LULC change between 2001/02 and 2018/19. Appendix E1 shows the volume of water yield (m^3/year) for the two study periods by LULC class. Seventeen out of the 19 LULC classes had a substantial reduction in water yield, which can mainly be attributed to lesser rainfall in 2018/19. The 52% reduction in water yield for exotic forests can be primarily attributed to rainfall reduction and the 18% reduction in the planted forest area. Consequently, the increase in water yield of 16% for dairying can be attributed mainly to an increase in land area of 84%, more than offsetting the reduction in rainfall in 2018/19 (Appendices D and E1). Overall, the study catchment had a lesser water yield of 332 million m^3, a 39% reduction. This is the exact same result in Table 6 which also presents our water yield estimates for the full study catchment. The overall percentage reductions in quickflow, local recharge and baseflow in Appendix E1 are the same as those presented in Table 7 for the full catchment.

Similar with the InVEST results at the sub-catchment level, we present in Appendices E2 and E3 the summary of InVEST results where we fixed the climatic and biophysical data for the wet and dry years and allowed the LULC classes to vary between 2001/02 and 2018/19. The difference here is that we summarised in these capacity accounts the results of InVEST water yield and seasonal water yield models for each study year by LULC class (and not by sub-catchment). We find a pattern that if we control mainly for the change in LULC, while excluding climatic difference, we find that the percentage change was less than a 1% reduction for all four measures of water flow regulation services. A reduction of 0.09% and 0.01% in water yield for 2001/02 and 2018/19 indicates that more water is reduced by land use change during the wet year. These results may appear to indicate that land use change, overall, leads to a very small reduction in water availability in the study catchment. However, if we convert 0.09% and 0.01% to the approximate volume of water, they are about 793,024 m^3/year and 76,592 m^3/year, respectively (Figure 12). The volume of water yield reduction in the wet and dry seasons is equivalent to the annual domestic water demand of 538 ha and 52 ha, respectively, of residential built-up areas in the catchment.

Assuming that a hectare of residential area has 12 residential homes, the above reduction in water yield volume corresponds to a year of domestic water supply for 10,760 households and 1,040 households, respectively. The above household numbers are similar to the 2022 medium growth scenario projected number of family households in Taupo and about 45% of Waitomo districts respectively (Waikato Regional Council, 2021).

Compared to water yield, local recharge and baseflow both had a greater reduction of more than 1,000,000 m^3 during the wet year and about 600,000 m^3 during the dry year (Figure 13). In terms of quickflow, approximately 437,085 m3 was reduced in the wet year and with a lesser reduction of 253,404 m^3 during the dry year. The above reductions in water flow regulation services should be accounted for in the catchment especially local recharge and baseflow which contributes to the supply of water during the months with lesser rainfall.

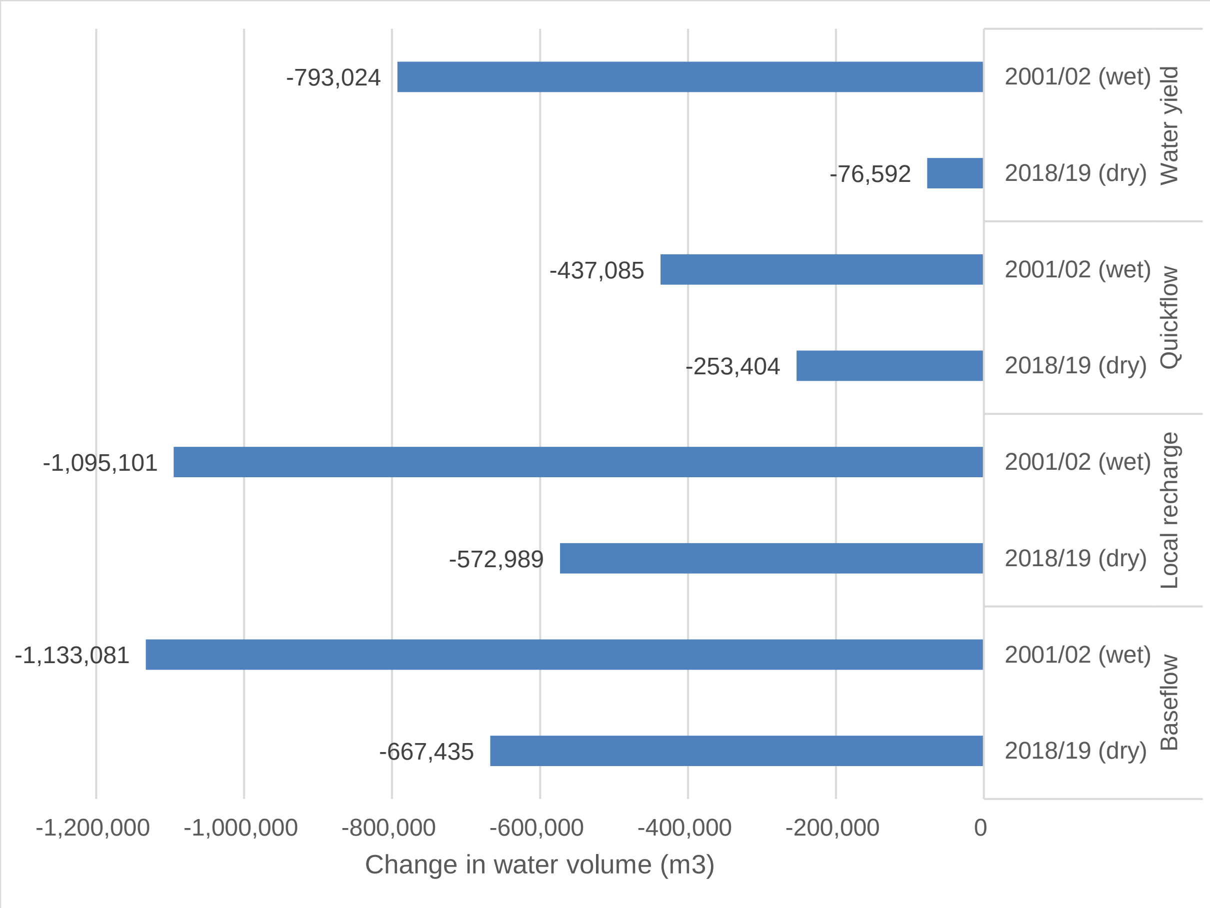


Figure 12. Change in the provision of water flow regulation ecosystem services due to LULC change.

Summary, conclusions and future directions

Summary and conclusions

To the best of our knowledge, this is the first New Zealand application of two InVEST models: Water Yield and Hydropower Valuation and Seasonal Water Yield. Although these models are relatively simplistic to other platforms (e.g. Soil and Water Assessment Tool (SWAT) (Arnold et al. 2012)), we have carefully constructed New Zealand climatic, soil and water demand data to run the models. We have also discussed our preliminary results with experts in the field who provided valuable suggestions on model applications and interpretation of results. Results from our spatial modelling exercise have been found to be robust and by referring to the literature, we found them to be consistent with studies on the impact of land use change on the provision of water flow regulation related ES.

This study has developed and applied a new framework to quantify land use change impacts on five water availability related ES. Analysis was undertaken at the sub-catchment level to evaluate the impacts on the provision of water flow related ES, particularly hydropower generation, an important source of renewable energy in New Zealand. Analysis was also undertaken by LULC class which enabled the creation of pilot ecosystem accounts for the 19 LULC classes under three different modelling scenarios: (1) impacts of LULC change between the two study years (2001/02 and 2018/19); (2) impacts of the change in LULC in the wet year (2001/02); and impacts of LULC change in the dry year (2018/19). Results were summarised systematically for informing decision-making processes. This assessment framework is illustrated as a flow diagram in Appendix F.

The quantitative results from this study may be used as indicators to discuss land use change and potential impact on water availability ES values in the region. WRC proposed the Waikato Progress Indicators (WPI) in August 2014 to inform the development of a “comprehensive assessment of economic, environmental and social wellbeing conditions and trends for the Waikato region” (Killerby and Huser 2014). WPI provides a set of indicators for the environmental aspect, including river water quality and indicators of water use and water allocation in a recent WPI report (Huser and Killerby 2021). However, that report does not yet include an indicator for river water availability. The results here could advance the development of a progress indicator for water flow regulation or water availability values in the region. This is increasingly important due to the impacts of climate change.

Sub-catchments with the least rate of conversion to more intensive land use had the smallest reduction in water yield during the wet year. The Aratiatia sub-catchment also had the least increase in water consumption and the lowest reduction in hydropower production. From the Seasonal Water Yield modelling, we found that Aratiatia had an increase in baseflow and local recharge in both wet and dry years while all the other sub-catchment decreased in the provision of those water flow regulation ES. The quickflow or floodflow in Aratiatia was also least affected by land use change. The above results show a more stable provision of water related ES in the sub-catchment with the least conversion to a more intensive land use.

The construction of two pilot ecosystem accounts (extent and capacity accounts) allowed us to present a set of data tables to show the impact of land use change in the study catchment across 19 major LULC classes. Overall, we found that the impact of type of land use change occurring within the study area was associated with a reduction in the provision of four water flow regulation ES. Although the impact in percentage terms appears small, it translates in real terms as reductions of water volume metrics as ‘equivalent water demand volume in built up environments’ enables a pragmatic illustration of the magnitude of the potential impacts to the community.

These accounts can serve as a starting point to develop a more comprehensive set of interrelated ecosystem accounts that may include water quality by LULC, water use by LULC and other relevant data to create detailed stock accounts and flow accounts. Relevant materials outlining the steps in developing these ecosystem accounts are described in many key publications (UN-SEEA 2021; Warnell et al. 2020; Bagstad, Ancona, et al. 2020). The natural capital accounting system, which includes ecosystem accounting, provides a framework to inform decision making with an additional set of ecosystem values i.e. economic use values that can be translated to exchange values (Vardon et al. 2018). However, environmental accounting ignores important non-use values (e.g., existence and bequest) and, therefore, may not provide the full picture of the value of an ecosystem (Pannell 2022). There are ongoing discussions and dialogues between accountants, statisticians, ecologists and natural resource economists to address this issue (Dasgupta 2021; Fenichel and Hashida 2019; Cavalletti and Corsi 2021).

The results presented in this report should be treated as indicative and not absolute. Although we have carefully collected and compiled the spatial data for the two InVEST models to the catchment study site, the parametrisation and calibration were challenging as some data were not readily accessible (e.g. river flow data, actual hydropower generation by catchment). In addition, some data needed to validate the results were not accessible as they are considered sensitive by some industries and/or individuals.

This study focused mainly on water regulation and did not examine the impact of land use change on water quality; the latter has already been extensively studied in New Zealand.

Future directions

We have used here the InVEST platform, a relatively simple open-sourced but widely used spatial model (Esse et al. 2021; Bagstad, Ingram, et al. 2020), to evaluate the impacts of freshwater related ES. Future studies should apply different methods to assess the impacts of land use change and examine the impacts on ES more comprehensively. This would help better understand the different methods for quantifying freshwater ES. This would lead to the standardisation or generalisation of the results to better incorporate the wider value of water availability and other non-market factors in decision making.

Spatial models in this space are continuously being improved, so applying them in a future project would allow for better quantification of freshwater ES as well as identify the values that are more suitable for informing specific decisions, accounting for or reporting of freshwater ES values. In addition, it would be helpful to compare InVEST model estimates with at least three other spatial models such as LUCI (Land Utilisation Capability Indicator), SWAT (Soil & Water Assessment Tool) and WATYIELD Water Balance Model to demonstrate their strengths and weaknesses in producing robust estimates of ES values. In this future spatial modelling work, it is important to include a calibration component to support the validity of estimates.

There is potential to develop hybrid approaches for the quantification of the full set of water related ES so as to come up with more accurate, detailed assessment of value to the economy, environment and society. This will allow for informed decision making for a sustainable and climate resilient future. Furthermore, it is also important to know what types and structures of information natural resource managers would actually use to inform their decision-making processes. Such information would help contribute to the design of future ES assessment frameworks and accounting systems.

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References

Ahiablame, Laurent, Aleksey Y. Sheshukov, Vahid Rahmani, and Daniel Moriasi. 2017. 'Annual baseflow variations as influenced by climate variability and agricultural land use change in the Missouri River Basin', *Journal of Hydrology*, 551: 188-202.

Allen, R. G., Pereira, L .S., Raes, D., Smith, M.,. 1998. "Crop evapotranspiration. Guidelines for computing crop water requirements." In *FAO Irrigation and Drainage Paper 56* Rome: Food and Agriculture Organization of the United Nations.

Aneseyee, Abreham Berta, Teshome Soromessa, Eyasu Elias, Tomasz Noszczyk, and Gudina Legese Feyisa. 2022. 'Evaluation of Water Provision Ecosystem Services Associated with Land Use/Cover and Climate Variability in the Winike Watershed, Omo Gibe Basin of Ethiopia', *Environmental Management*, 69: 367-83.

Archer, Michelle, Hannah Palmer, and Angus McKenzie. 2019. "Upper Waikato Zone Plan: Te mahere ā-rohe o Waikato ki runga." In, 42. Hamilton: Waikato Regional Council.

Arnold, J.G., J.R. Kiniry, R. Srinivasan, J.R. Williams, E.B. Haney, and S.L. Neitsch. 2012. *Soil and water assessment tool* (Texas Water Resource Institute).

Assure Quality. 2022. "Agribase." In, edited by Assure Quality.

Aylward, Bruce, Jayanta Bandyopadhyay, Juan-Carlos Belausteguigotia, Peter Borkey, AZ Cassar, Laura Meadors, Lilian Saade, Mark Siebentritt, Robyn Stein, and S Tognetti. 2005. 'Freshwater ecosystem services', *Ecosystems and human well-being: policy responses*, 3: 213-56.

Bagstad, Kenneth J., Zachary H. Ancona, Julie Hass, Pierre D. Glynn, Scott Wentland, Michael Vardon, and John Fay. 2020. 'Integrating physical and economic data into experimental water accounts for the United States: Lessons and opportunities', *Ecosystem Services*, 45: 101182.

Bagstad, Kenneth J., Jane Carter Ingram, Glenn-Marie Lange, Michel Masozera, Zachary H. Ancona, Mediatrice Bana, Desire Kagabo, Bernard Musana, Nsharwasi Leon Nabahungu, Emmanuel Rukundo, Evariste Rutebuka, Stephen Polasky, Denis Rugege, and Claudine Uwera. 2020. 'Towards ecosystem accounts for Rwanda: Tracking 25 years of change in flows and potential supply of ecosystem services', *People and Nature*, 2: 163-88.

Baillie, B.R., and R.T. Yao. 2015. "Pilot study on the freshwater ecosystem services provided by wadeable and non-wadeable streams in the Waikato river catchment." In *A report commissioned by the Waikato Regional Council.* , 21. Hamilton, New Zealand: Scion.

Baillie, B.R., R.T. Yao, and D.J. Palmer. 2020. "Ohinemuri catchment – river and streams ecosystem services assessment." In *Technical Report 2019/25*, 62. Hamilton, New Zealand: Waikato Regional Council

Bateman, Ian J., and Georgina M. Mace. 2020. 'The natural capital framework for sustainably efficient and equitable decision making', *Nature Sustainability*, 3: 776-83.

Blaschke, P. M., D. L. Hicks, and A. Meister. 2008. "Quantification of the flood and erosion reduction benefits, and costs, of climate change mitigation measures in New Zealand." In, edited by Blaschke and Rutherford Environmental Consultants. Wellington: Ministry for the Environment.

Brauman, Kate A., Lucas A. Garibaldi, Stephen Polasky, Yildiz Aumeeruddy-Thomas, Pedro H. S. Brancalion, Fabrice DeClerck, Ute Jacob, Matias Enrique Mastrangelo, Nsalambi V. Nkongolo, Hannes Palang, Néstor Pérez-Méndez, Lynne J. Shannon, Uttam Babu Shrestha, Evelyn Strombom, and Madhu Verma. 2020. 'Global trends in nature's contributions to people', *Proceedings of the National Academy of Sciences*, 117: 32799-805.

Canadell, J., R. B. Jackson, J. B. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze. 1996. 'Maximum rooting depth of vegetation types at the global scale', *Oecologia*, 108: 583-95.

Cavalletti, Barbara, and Matteo Corsi. 2021. 'The system of environmental and economic accounting and the valuation problem: a review of the literature', *Journal of Environmental Planning and Management*: 1-30.

Clausen, B, and BJF Biggs. 1997. 'Relationships between benthic biota and hydrological indices in New Zealand streams', *Freshwater Biology*, 38: 327–42.

Columbus, J., P. Sirguey, and R. Tenzer. 2011. 'A free, fully assessed 15-m DEM for New Zealand', *Survey Quarterly*, 66: 16-19.

Dasgupta, P. . 2021. "The Economics of Biodiversity: The Dasgupta Review." In. London: HM Treasury.

Davie, T, and B Fahey. 2005. 'Forestry and water yield - current knowledge and futher work', *New Zealand Journal of Forestry*, 49 3–8.

Destremau, Killian, and Prince Siddharth. 2018. "How does the dairy sector share its growth? An analysis of the flow-on benefits of dairy's revenue generation." In *NZIER report to Dairy Companies Association of New Zealand*, edited by John Ballingall, 37. Wellington: New Zealand Institute of Economic Research.

Ding, Jiao, Yuan Jiang, Lan Fu, Qi Liu, Qiuzhi Peng, and Muyi Kang. 2015. 'Impacts of Land Use on Surface Water Quality in a Subtropical River Basin: A Case Study of the Dongjiang River Basin, Southeastern China', *Water*, 7.

Donohue, Randall J., Michael L. Roderick, and Tim R. McVicar. 2012. 'Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model', *Journal of Hydrology*, 436-437: 35-50.

Duncan, Maurice J., and Ross A. Woods. 2013. 'Water regulation.' in John Dymond (ed.), *Ecosystem Services in New Zealand: Conditions and Trends* (Manaaki Whenua Press: Lincoln).

Ennaanay, Driss. 2006. 'Impacts of Land Use Changes on the Hydrologic Regime in the Minnesota River Basin', PhD thesis, University of Minnesota.

ESRI. 2022. "ArcGIS Pro." In, edited by ESRI. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

Esse, Carlos, Ney Ríos, Pablo Saavedra, David Fonseca, Francisco Encina-Montoya, Rodrigo Santander-Massa, Patricio De los Ríos-Escalante, Guillermo Figueroa-Muñoz, Adolfo López-Pérez, and Francisco Correa-Araneda. 2021. 'Effects of land use change on water availability and water efficiency in the temperate basins of south-central Chile', *Journal of King Saud University - Science*, 33: 101650.

Fahey, Barry, Jagath Ekanayake, Rick Jackson, Andrew Fenemor, Tim Davie, and Lindsay Rowe. 2010. 'Using the WATYIELD water balance model to predict catchment water yields and low flows', *Journal of Hydrology (NZ)*, 49: 35-58.

Fenichel, Eli P, and Yukiko Hashida. 2019. 'Choices and the value of natural capital', *Oxford Review of Economic Policy*, 35: 120-37.

Gardiner, Dylan, and Beat Huser. 2017. "Applying an ecosystem services approach to policy development: Opportunities, benefits and recommended approach for Waikato Regional Council." In, 54. Hamilton, New Zealand: Waikato Regional Council.

Griffiths, E. . 1985. "Interpretation of soil morphology for assessing moisture movement and storage." In *New Zealand Soil Bureau Scientific Report 74*, 20. New Zealand Soil Bureau

Grizzetti, B., D. Lanzanova, C. Liquete, A. Reynaud, and A. C. Cardoso. 2016. 'Assessing water ecosystem services for water resource management', *Environmental Science & Policy*, 61: 194-203.

Hamel, P., and A. J. Guswa. 2015. 'Uncertainty analysis of a spatially explicit annual water-balance model: case study of the Cape Fear basin, North Carolina', *Hydrol. Earth Syst. Sci.*, 19: 839-53.

Hamilton City Council. undated. 'River to the Tap: A Guide to Hamilton's Water Supply', Hamilton City Council, Accessed 2 February 2022. https://www.hamilton.govt.nz/our-services/water/water/Documents/A%20Guide%20to%20Hamilton%E2%80%99s%20Water%20Supply.pdf.

Higham, C. D., D. Horne, R. Singh, B. Kuhn-Sherlock, and M. R. Scarsbrook. 2017. 'Temporal and spatial water use on irrigated and nonirrigated pasture-based dairy farms', *Journal of Dairy Science*, 100: 6772-84.

Huser, Beat, and Paul Killerby. 2021. "Waikato progress indicators – Tupuranga Waikato (Summary update June 2021)." In *Technical Report 2021/12*, 20. Hamilton: Waikato Regional Council

Journeaux, P. 2020. "Financial Survey 2020 Waikato/Bay of Plenty Dairy." In. Hamilton: AgFirst Hamilton/Rotorua Limited.

Keeler, Bonnie L, Stephen Polasky, Kate A Brauman, Kris A Johnson, Jacques C Finlay, Ann O'Neill, Kent Kovacs, and Brent Dalzell. 2012. 'Linking water quality and well-being for improved assessment and valuation of ecosystem services', *Proceedings of the National Academy of Sciences*, 109: 18619-24.

Khan, Imran, and Minjuan Zhao. 2019. 'Water resource management and public preferences for water ecosystem services: A choice experiment approach for inland river basin management', *Science of The Total Environment*, 646: 821-31.

Kibena, J., I. Nhapi, and W. Gumindoga. 2014. 'Assessing the relationship between water quality parameters and changes in landuse patterns in the Upper Manyame River, Zimbabwe', *Physics and Chemistry of the Earth, Parts A/B/C*, 67-69: 153-63.

Killerby, Paul, and Beat Huser. 2014. "Development of the Waikato Progress Indicators (WPI)." In *Waikato Regional Council Technical Report 2014/44*, 113. Hamilton: Waikato Regional Council

Kumar, Pushpam. 2018. 'GDP is no longer an accurate measure of economic progress. Here's why', Accessed January 16. https://www.weforum.org/agenda/2018/11/forget-gdp-for-the-21st-century-we-need-a-modern-economic-measure.

La Notte, Alessandra, Sara Vallecillo, and Joachim Maes. 2019. 'Capacity as "virtual stock" in ecosystem services accounting', *Ecological Indicators*, 98: 158-63.

Landcare Research. 2020. "LCDB v5.0 - Land Cover Database version 5.0, Mainland, New Zealand." In, edited by Landcare Research New Zealand Ltd. LRIS.

León-Muñoz, J., C. Echeverría, R. Marcé, W. Riss, B. Sherman, and J. L. Iriarte. 2013. 'The combined impact of land use change and aquaculture on sediment and water quality in oligotrophic Lake Rupanco (North Patagonia, Chile, 40.8°S)', *J Environ Manage*, 128: 283-91.

LRIS. 2010. 'Fundamental Soil Layer: Depth to Slowly Permeable Horizon', Land Resource Information System, Accessed 14 March 2022. https://lris.scinfo.org.nz/layer/48108-fsl-depth-to-slowly-permeable-horizon/.
Madgwick, H.A.I. 1994. *Pinus radiata: Biomass, form and growth* (CABI: Rotorua).
McConchie, Jack. 2001. 'Water transport processes.' in Andrew Sturman and Rachel Spronken-Smith (ed.), *The Physical Environment: A New Zealand Perspective* (Oxford University Press: Auckland).
MEA. 2005. "Ecosystems and Human Well-being: Biodiversity Synthesis (Millennium Ecosystem Assessment)." In. Washington, DC, USA: World Resources Institute.
Mercury. 2019. "Our annual report 2019." In, 125. Auckland: Mercury NZ Limited.
Mighty River Power. 2002. "Mighty River Power Annual Report 2002." In, 87. Auckland: Mighty River Power
NIWA Project Team. 2010. "Waikato River independent scoping study " In *NIWA Client Report: HAM2010-032*, 265. Hamilton: National Institue of Water & Atmospheric Research Ltd.
Pannell, David. 2022. 'Environmental accounting: is it worthwhile?', Accessed 22 February 2022. https://www.pannelldiscussions.net/2022/02/366-environmental-accounting/.
Peh, Kelvin S. H., Andrew Balmford, Richard B. Bradbury, Claire Brown, Stuart H. M. Butchart, Francine M. R. Hughes, Alison Stattersfield, David H. L. Thomas, Matt Walpole, Julian Bayliss, David Gowing, Julia P. G. Jones, Simon L. Lewis, Mark Mulligan, Bhopal Pandeya, Charlie Stratford, Julian R. Thompson, Kerry Turner, Bhaskar Vira, Simon Willcock, and Jennifer C. Birch. 2013. 'TESSA: A toolkit for rapid assessment of ecosystem services at sites of biodiversity conservation importance', *Ecosystem Services*, 5: 51-57.
River & Catchment Services Group, and GHD Limited 2010. 2011. "Overview of River and Catchment Services – Waikato Region." In, 26. Hamilton: Waikato Regional Council.
Running, S., Q. Mu, M. Zhao, and A. Moreno. 2019. "MOD16A2GF MODIS/Terra Net Evapotranspiration Gap-Filled 8-Day L4 Global 500 m SIN Grid V006 [Data set].
." In, edited by NASA EOSDIS Land Processes DAAC.
Seifert-Dähnn, Isabel, Line Johanne Barkved, and Eduard Interwies. 2015. 'Implementation of the ecosystem service concept in water management–Challenges and ways forward', *Sustainability of Water Quality and Ecology*, 5: 3-8.
Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D.,, D. Fisher, Glowinski, K., Griffin, R., Guannel, G., Guerry, A., Johnson, J., Hamel, P., Kennedy, C., Kim, C.K.,, and M. Lacayo, Lonsdorf, E., Mandle, L., Rogers, L., Silver, J., Toft, J., Verutes, G., Vogl, A. L., Wood, S, and Wyatt, K. 2020. "InVEST 3.9.0.post45+ug.g162427b.d20210309 User's Guide." In. Stanford, CA, USA: The Natural Capital Project.
Sharp, R., H.T. Tallis, T. Ricketts, A.D. Guerry, S.A. Wood, R. Chaplin-Kramer, E. Nelson, and et al. 2018. 'InVEST 3.6.0 User's Guide', Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund, Accessed 31 March 2019. http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/InVEST_3.6.0_Documentation.pdf.
Snelder, T.H., M. Weatherhead, and B.J.F. Biggs. 2004. "New Zealand River Environment Classification User Guide. Updated in September 2010. ." In *Publication number: ME 1026* Wellington: Ministry for the Environment.
Statistics New Zealand. undated. '
Meshblock 2018 (generalised)', Statistics New Zealand, Accessed 2 February 2022. https://datafinder.stats.govt.nz/data/#:~:text=compared%20over%20time.-,A%20meshblock%20is%20the%20smallest%20geographic%20unit%20for%20which%20statistical,large%20area%20of%20rural%20land.
Trodahl, Martha I., Bethanna M. Jackson, Julie R. Deslippe, and Alister K. Metherell. 2017. 'Investigating trade-offs between water quality and agricultural productivity using the Land Utilisation and Capability Indicator (LUCI)–A New Zealand application', *Ecosystem Services*, 26: 388-99.
UKNEA. 2011. "The UK National Ecosystem Assessment: Synthesis of the Key Findings." In. Cambridge: UNEP-WCMC.
UN-SEEA. 2021. 'Ecosystem Accounting', UN System of Environmental Economic Accounting, Accessed 15 March. https://seea.un.org/ecosystem-accounting.
Vardon, Michael, Juan-Pablo Castaneda, Michael Nagy, and Sjoerd Schenau. 2018. 'How the System of Environmental-Economic Accounting can improve environmental information systems and data quality for decision making', *Environmental Science & Policy*, 89: 83-92.
Waikato Regional Council. 2016. "Proposed Waikato regional plan change 1 - Waikato and Waipā River catchments." In, 120. Hamilton: Waikato Regional Council.
Waikato Regional Council, 2021. 2018-based Population, Family and Household, and Labour Force Projections for the Waikato Region, 2018 – 2068.Waikato Regional Council Technical Report 2021/22. Accessed online 17/10/2022, https://www.waikatoregion.govt.nz/assets/WRC/WRC-2019/TR202122.pdf

———. undated. 'About the Waikato region', Waikato Regional Council. https://www.waikatoregion.govt.nz/community/about-the-waikato-region/.

Warnell, Katherine J. D., Marc Russell, Charles Rhodes, Kenneth J. Bagstad, Lydia P. Olander, David J. Nowak, Rajendra Poudel, Pierre D. Glynn, Julie L. Hass, Satoshi Hirabayashi, Jane Carter Ingram, John Matuszak, Kirsten L. L. Oleson, Stephen M. Posner, and Ferdinando Villa. 2020. 'Testing ecosystem accounting in the United States: A case study for the Southeast', *Ecosystem Services*, 43: 101099.

WAVES. Undated. 'Frequently Asked Questions on Natural Capital Accounting (NCA)', Wealth Accounting and the Valuation of Ecosystem Services, Accessed 8 March. https://www.wavespartnership.org/en/frequently-asked-questions-natural-capital-accounting-nca#:~:text=Natural%20Capital%20Accounts%20(NCA)%20are,as%20forests%2C%20energy%20and%20water.

Webb, T. H., and A. D. Wilson. 1995. "A manual of land characteristics for evaluation of rural land." In *Landcare Research Science Series 10*, 32. Lincoln: Manaaki Whenua Landcare Research.

Wei, Peijie, Shengyun Chen, Minghui Wu, Yanfang Deng, Haojie Xu, Yinglan Jia, and Fang Liu. 2021. 'Using the InVEST Model to Assess the Impacts of Climate and Land Use Changes on Water Yield in the Upstream Regions of the Shule River Basin', *Water*, 13: 1250.

Woods, Ross, Ian Jowett, Rory Nathan, Jon Williamson, Alan Pattle, Murray Mulholland, Ghassan Basheer, Daniel Collins, Jochen Schmidt, John Hansford, Blair Thornborrow, and Steven Joynes. 2010. "Summary of the effects of land use change between Taupō and Karapiro on the flood hydrology of the Waikato River catchment." In *Environment Waikato Technical Report 2009/21*, 112. Hamilton: Environment Waikato.

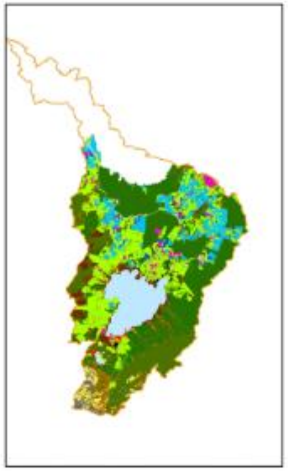
World Commission on Dams. 2000. "Dams and development: A new framework for decision-making." In *The Report of the World Commission on Dams*. London.

Wratt, D. S., A. Tait, G. Griffiths, P. Espie, M. Jessen, J. Keys, M. Ladd, D. Lew, W. Lowther, N. Mitchell, J. Morton, J. Reid, S. Reid, A. Richardson, J. Sansom, and U. Shankar. 2006. 'Climate for crops: integrating climate data with information about soils and crop requirements to reduce risks in agricultural decision-making', *Meteorological Applications*, 13: 305-15.

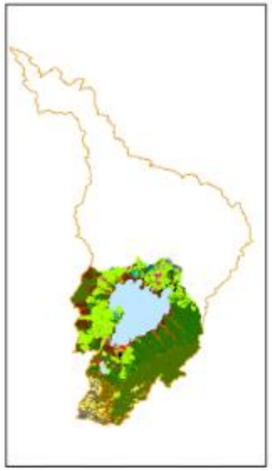
Yao, R. T., D. R. Harrison, S. J. Velarde, and L. E. Barry. 2016. 'Validation and enhancement of a spatial economic tool for assessing ecosystem services provided by planted forests', *Forest Policy and Economics*, 72: 122-31.

Yao, R.T., and S.J. Velarde. 2014. "Ecosystem services in the Ōhiwa catchment." In *A commissioned report submitted by Scion to the Bay of Plenty Regional Council*. Whakatane, New Zealand: Bay of Plenty Regional Council.

Appendix A1 - Land use / Land cover distribution (%) in 2001/02 by sub-catchment



Arapuni



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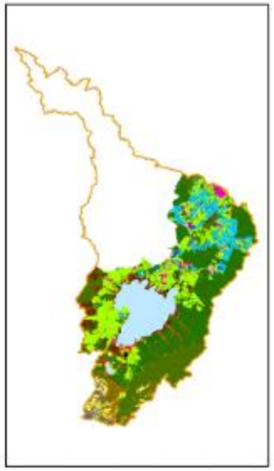

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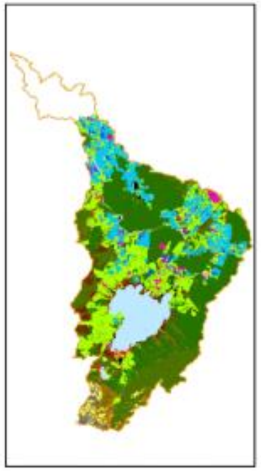
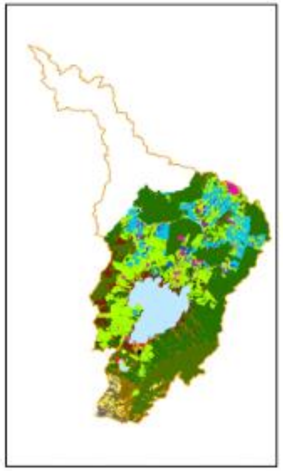
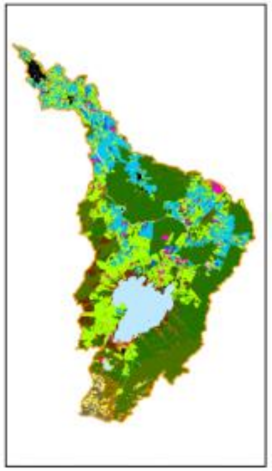


Karapiro



Maraetai 1&2



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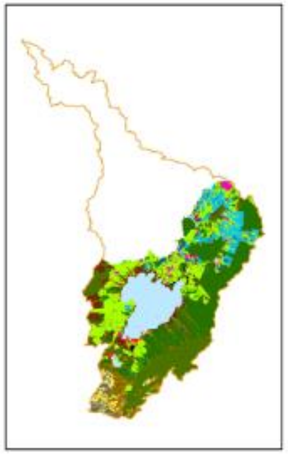
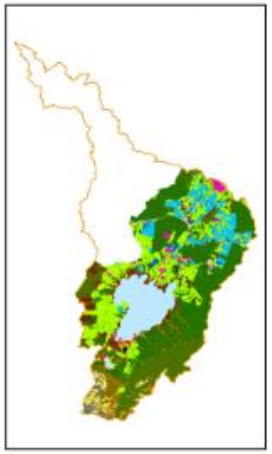
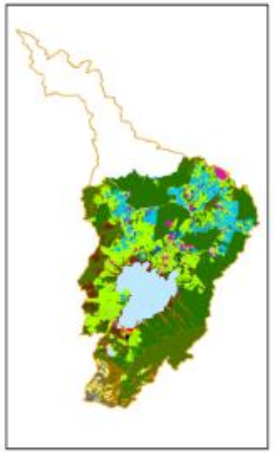


Ohakuri

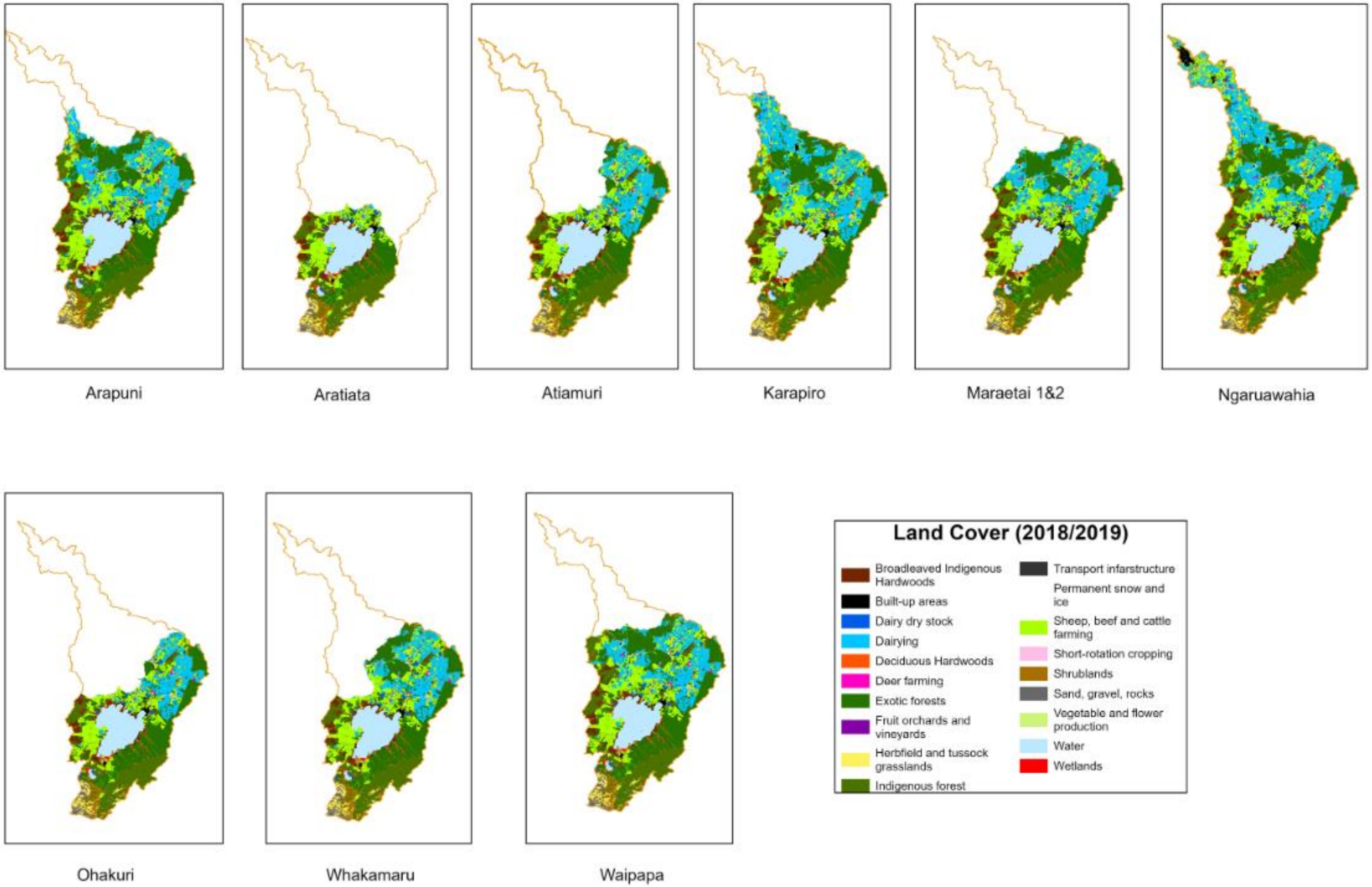


Whakamaru



Waipapa

Appendix A2 - Land use / Land cover distribution (%) in 2018/19 by sub-catchment



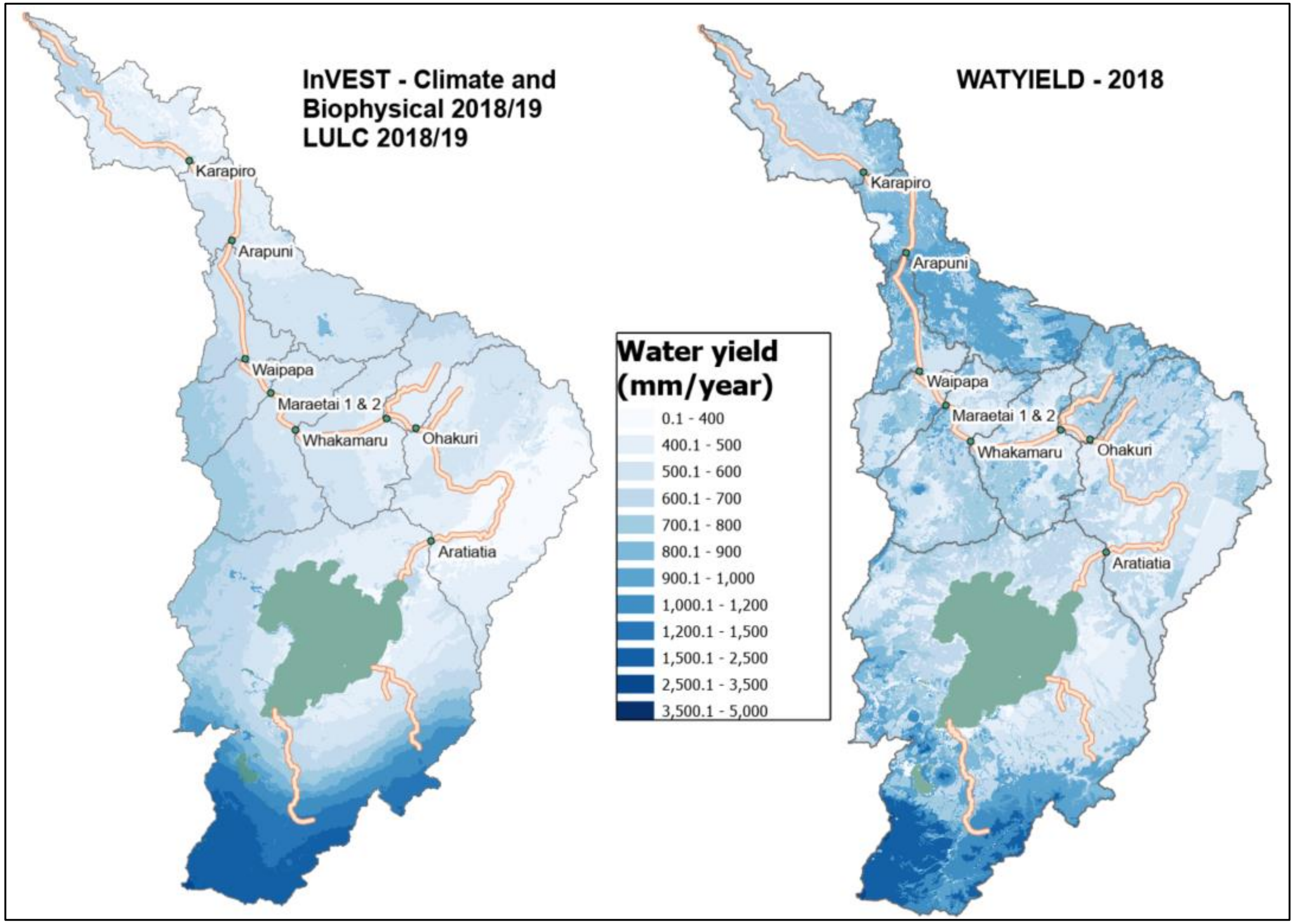
Appendix B

Proportion (%) of land-use area by sub-catchment over the two time periods.

Land use / Land cover	Arapuni		Aratiatia		Ātiamuri		Karapiro		Maraetai_1_2		Ohakuri		Waipapa		Whakamaru		Full catchment	
	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19	2001/02	2018/19
Exotic forests	31.2	26.5	19.6	21.3	28.2	24.5	31.6	25.8	31.5	26.7	27.8	24.4	31.3	26.6	31.0	26.6	29.5	24.1
Sheep, beef and cattle farming	21.9	18.5	19.5	16.9	20.6	17.4	21.2	18.0	21.4	18.3	20.4	17.3	21.6	18.3	20.8	17.8	22.7	19.4
Indigenous forest	14.0	13.8	20.2	20.1	14.9	14.8	13.1	12.9	13.5	13.4	15.1	14.9	14.4	14.2	13.7	13.6	12.3	12.1
Dairying	7.7	16.7	0.5	0.9	6.4	13.7	10.6	20.6	7.3	16.0	5.7	12.3	7.2	15.8	6.6	14.7	11.6	21.4
Water	9.7	9.7	17.9	17.9	12.3	12.3	8.8	8.8	10.3	10.3	12.9	12.9	9.9	9.9	11.3	11.3	8.3	8.3
Shrublands	4.9	4.8	8.0	7.9	5.7	5.6	4.4	4.3	4.8	4.7	5.9	5.9	4.9	4.9	5.2	5.2	4.1	4.0
Broadleaved indigenous hardwoods	4.1	4.1	6.2	6.2	4.6	4.5	3.8	3.7	4.4	4.4	4.8	4.8	4.3	4.2	4.3	4.2	3.6	3.5
Dairy dry stock	1.0	1.4	0.3	1.2	0.8	1.4	1.3	1.6	1.0	1.4	0.8	1.4	1.0	1.3	0.9	1.3	1.7	1.9
Deer farming	1.4	0.4	0.7	0.2	1.3	0.4	1.4	0.4	1.4	0.4	1.2	0.4	1.3	0.4	1.4	0.4	1.4	0.4
Built-up areas	0.4	0.6	0.6	1.0	0.5	0.7	0.5	0.6	0.4	0.6	0.5	0.7	0.4	0.6	0.4	0.6	1.4	1.6
Herbfield and tussock grasslands	1.7	1.7	3.3	3.3	2.2	2.2	1.5	1.5	1.8	1.8	2.3	2.3	1.7	1.7	2.0	2.0	1.4	1.4
Permanent snow and ice	1.1	1.1	2.1	2.1	1.4	1.4	1.0	1.0	1.2	1.2	1.5	1.5	1.1	1.1	1.3	1.3	0.9	0.9
Wetlands	0.4	0.4	0.6	0.6	0.5	0.5	0.4	0.3	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.4	0.4	0.3
Deciduous hardwoods	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.2
Short-rotation cropping	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Fruit orchards and vineyards	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Sand, gravel, rocks	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Vegetable and flower production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Transport infrastructure	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix C

InVEST Water Yield 2018/19 versus WATYIELD 2018



Appendix D

Pilot ecosystem extent account

		Ecosystem Type (Land Use/Land Cover Class)																			
		Broadleaved indigenous hardwoods	Built-up areas	Dairy dry stock	Dairying	Deciduous hardwoods	Deer farming	Exotic forests	Fruit orchards and vineyards	Herbfield and tussock grasslands	Indigenous forest	Sand, gravel, rocks	Transport infrastructure	Sheep, beef and cattle farming	Short-rotation cropping	Shrublands	Permanent snow and ice	Vegetable and flower production	Water	Wetlands	Total
Area (ha)	2001/02	29,830.7	11,671.8	14,574.9	97,542.5	2,045.1	11,911.7	247,609.3	680.5	11,639.5	103,282.0	662.7	102.8	190,034.1	1,952.3	34,410.0	7,794.2	456.8	69,230.7	3,072.7	838,504.5
	2018/19	29,362.8	13,592.1	15,578.2	179,206.2	1,747.6	3,637.8	201,852.0	847.7	11,639.6	101,556.7	614.0	102.8	162,470.9	1,921.5	33,824.0	7,788.6	800.6	69,193.9	2,767.4	838,504.5
	Area change (2018/19 less 2001/02)	-467.9	1,920.4	1,003.3	81,663.7	-297.5	-8,273.9	-45,757.4	167.2	0.0	-1,725.4	-48.7	0.0	-27,563.2	-30.8	-586.0	-5.6	343.7	-36.8	-305.2	
% change [(2018/19 less 2001/02) ÷ (2001/02)]		-1.6	16.5	6.9	83.7	-14.5	-69.5	-18.5	24.6	0.0	-1.7	-7.3	0.0	-14.5	-1.6	-1.7	-0.1	75.2	-0.1	-9.9	

Appendix E1

Pilot ecosystem capacity account for 2001/02 and 2018/19

		Ecosystem Type (Land Use/Land Cover (LULC) Class)																			
		Broadleaved indigenous hardwoods	Built-up areas	Dairy dry stock	Dairying	Deciduous hardwoods	Deer farming	Exotic forests	Fruit orchards and vineyards	Herbfield and tussock grasslands	Indigenous forest	Sand, gravel, rocks	Transport infrastructure	Sheep, beef and cattle farming	Short-rotation cropping	Shrublands	Permanent snow and ice	Vegetable and flower production	Water	Wetlands	Total
Water yield ('000 m3/year)	Biophysical, climate & LULC 2001/02	30,042	10,895	10,506	75,633	1,792	9,949	229,839	380	29,861	158,010	867	463	170,230	1,320	57,831	20,485	296	33,446	3,354	845,199
	Biophysical, climate & LULC 2018/19	17,817	9,179	8,243	87,975	946	1,763	111,359	330	20,900	95,965	543	320	91,289	935	37,086	13,637	421	12,780	1,823	513,309
	Change in water yield (2018/19 less 2001/02)	-12,225	-1,717	-2,263	12,342	-846	-8,186	-118,480	-50	-8,961	-62,045	-324	-142	-78,941	-384	-20,745	-6,849	124	-20,666	-1,531	-331,890
	% change = [Change ÷ (2001/02)] X 100%	-40.69	-15.76	-21.54	16.32	-47.20	-82.28	-51.55	-13.10	-30.01	-39.27	-37.42	-30.80	-46.37	-29.12	-35.87	-33.43	41.96	-61.79	-45.64	-39.27
Quickflow ('000 m3/year)	Biophysical, climate & LULC 2001/02	2,215	1,225	783	5,960	842	556	11,932	37	7,076	7,297	213	412	12,632	206	5,488	8,573	47	74,197	3,874	143,564
	Biophysical, climate & LULC 2018/19	1,386	967	689	7,996	542	117	7,021	36	3,542	4,980	99	278	7,738	132	3,423	4,802	66	60,149	2,420	106,381
	Change in quickflow (2018/19 less 2001/02)	-829	-258	-95	2,036	-300	-439	-4,911	-1	-3,534	-2,317	-113	-134	-4,894	-74	-2,065	-3,771	19	-14,048	-1,455	-37,183
	% change = [Change ÷ (2001/02)] X 100%	-37.44	-21.03	-12.11	34.15	-35.60	-78.96	-41.16	-2.81	-49.94	-31.76	-53.36	-32.52	-38.74	-35.92	-37.63	-43.99	39.23	-18.93	-37.55	-25.90
Local recharge ('000 m3/year)	Biophysical, climate & LULC 2001/02	27,276	9,661	9,038	65,304	812	8,949	214,856	320	21,568	149,808	654	51	150,119	949	51,515	11,924	188	-7,165	-1,283	714,546
	Biophysical, climate & LULC 2018/19	15,703	8,176	6,827	71,400	262	1,489	100,103	256	15,817	89,662	442	42	76,526	630	32,605	8,834	255	-5,689	-1,276	422,061
	Change in local recharge (2018/19 less 2001/02)	-11,574	-1,485	-2,211	6,095	-551	-7,461	-114,754	-65	-5,751	-60,145	-212	-9	-73,593	-319	-18,910	-3,090	67	1,476	7	-292,485
	% change = [Change ÷ (2001/02)] X 100%	-42.43	-15.37	-24.46	9.33	-67.80	-83.37	-53.41	-20.20	-26.67	-40.15	-32.46	-16.81	-49.02	-33.64	-36.71	-25.92	35.86	-20.60	-0.52	-40.93
Baseflow ('000 m3/year)	Biophysical, climate & LULC 2001/02	27,968	9,815	9,332	67,644	1,130	9,138	218,907	337	21,690	151,354	661	51	153,875	1,011	52,630	12,089	200	19	0	737,851
	Biophysical, climate & LULC 2018/19	16,350	8,358	7,119	75,510	535	1,539	103,609	276	15,956	91,343	449	42	79,883	681	33,763	9,030	275	14	0	444,732
	Change in baseflow (2018/19 less 2001/02)	-11,619	-1,457	-2,213	7,866	-595	-7,599	-115,298	-62	-5,733	-60,011	-213	-9	-73,992	-330	-18,867	-3,058	75	-5	0	-293,119
	% change = [Change ÷ (2001/02)] X 100%	-41.54	-14.85	-23.71	11.63	-52.68	-83.16	-52.67	-18.28	-26.43	-39.65	-32.15	-16.81	-48.09	-32.66	-35.85	-25.30	37.66	-26.53	4.36	-39.73

Appendix E2

Pilot ecosystem capacity account for the wet year (2001/02)

		Ecosystem Type (Land Use/Land Cover (LULC) Class)																			
		Broadleaved indigenous hardwoods	Built-up areas	Dairy dry stock	Dairying	Deciduous hardwoods	Deer farming	Exotic forests	Fruit orchards and vineyards	Herbfield and tussock grasslands	Indigenous forest	Sand, gravel, rocks	Transport infrastructure	Sheep, beef and cattle farming	Short-rotation cropping	Shrublands	Permanent snow and ice	Vegetable and flower production	Water	Wetlands	Total
Water yield ('000 m3/year)	LULC 2001/02	30,042	10,895	10,506	75,633	1,792	9,949	229,839	380	29,861	158,010	867	463	170,230	1,320	57,831	20,485	296	33,446	3,354	845,199
	LULC 2018/19	29,690	12,424	12,871	143,474	1,520	2,799	192,722	466	29,861	156,164	787	463	145,311	1,312	57,000	20,495	502	33,426	3,118	844,406
	Change in water yield (2018/19 less 2001/02)	-352	1,528	2,365	67,841	-273	-7,150	-37,117	86	0	-1,845	-80	0	-24,918	-8	-831	10	206	-20	-236	-793
	% change = [Change ÷ (2001/02)] X 100%	-1.17	14.03	22.51	89.70	-15.21	-71.86	-16.15	22.50	0.00	-1.17	-9.23	0.00	-14.64	-0.58	-1.44	0.05	69.62	-0.06	-7.02	-0.09
Quickflow ('000 m3/year)	LULC 2001/02	2,215	1,225	783	5,960	842	556	11,932	37	7,076	7,297	213	412	12,632	206	5,488	8,573	47	74,197	3,874	143,564
	LULC 2018/19	1,971	1,342	952	10,484	708	158	9,693	42	7,076	7,154	191	412	10,993	184	5,362	8,587	73	74,167	3,580	143,127
	Change in quickflow (2018/19 less 2001/02)	-244	117	169	4,524	-133	-398	-2,239	5	0	-143	-22	0	-1,639	-23	-126	15	26	-30	-295	-437
	% change = [Change ÷ (2001/02)] X 100%	-11.03	9.54	21.55	75.90	-15.86	-71.59	-18.76	13.58	0.00	-1.96	-10.30	0.00	-12.98	-10.94	-2.30	0.17	54.94	-0.04	-7.61	-0.30
Local recharge ('000 m3/year)	LULC 2001/02	27,276	9,661	9,038	65,304	812	8,949	214,856	320	21,568	149,808	654	51	150,119	949	51,515	11,924	188	-7,165	-1,283	714,546
	LULC 2018/19	27,180	11,071	11,256	125,678	683	2,504	180,446	388	21,568	148,117	596	51	128,194	961	50,839	11,919	319	-7,185	-1,136	713,451
	Change in local recharge (2018/19 less 2001/02)	-97	1,410	2,218	60,374	-129	-6,445	-34,410	68	0	-1,691	-58	0	-21,924	12	-676	-5	132	-20	147	-1,095
	% change = [Change ÷ (2001/02)] X 100%	-0.35	14.60	24.54	92.45	-15.91	-72.02	-16.02	21.23	0.00	-1.13	-8.88	0.00	-14.60	1.28	-1.31	-0.04	70.25	0.28	-11.44	-0.15
Baseflow ('000 m3/year)	LULC 2001/02	27,968	9,815	9,332	67,644	1,130	9,138	218,907	337	21,690	151,354	661	51	153,875	1,011	52,630	12,089	200	19	0	737,851
	LULC 2018/19	27,775	11,242	11,549	129,753	950	2,554	183,643	409	21,690	149,617	602	51	131,502	1,015	51,920	12,087	341	19	0	736,718
	Change in baseflow (2018/19 less 2001/02)	-193	1,427	2,217	62,108	-180	-6,584	-35,264	72	0	-1,737	-59	0	-22,373	4	-710	-2	141	0	-0	-1,133
	% change = [Change ÷ (2001/02)] X 100%	-0.69	14.54	23.75	91.82	-15.90	-72.05	-16.11	21.29	0.00	-1.15	-8.92	0.00	-14.54	0.35	-1.35	-0.02	70.58	0.02	-11.32	-0.15

Appendix E3

Pilot ecosystem capacity account for the dry year (2018/19)

		Ecosystem Type (Land Use/Land Cover (LULC))																				
		Broadleaved indigenous hardwoods	Built-up areas	Dairy dry stock	Dairying	Deciduous hardwoods	Deer farming	Exotic forests	Fruit orchards and vineyards	Herbfield and tussock grasslands	Indigenous forest	Sand, gravel, rocks	Transport infrastructure	Sheep, beef and cattle farming	Short-rotation cropping	Shrublands	Permanent snow and ice	Vegetable and flower production	Water	Wetlands	Total
Water yield ('000 m3/year)	LULC 2001/02	18,038	7,967	6,895	47,135	1,101	6,265	132,650	267	20,899	97,074	593	320	107,024	939	37,603	13,631	242	12,783	1,959	513,386
	LULC 2018/19	17,817	9,179	8,243	87,975	946	1,763	111,359	330	20,900	95,965	543	320	91,289	935	37,086	13,637	421	12,780	1,823	513,309
	Change in water yield (2018/19 less 2001/02)	-221	1,212	1,349	40,840	-155	-4,502	-21,291	63	0	-1,109	-51	0	-15,735	-4	-517	6	179	-3	-136	-77
	% change = [Change ÷ (2001/02)] X 100%	-1.23	15.21	19.56	86.64	-14.05	-71.86	-16.05	23.78	0.00	-1.14	-8.53	0.00	-14.70	-0.42	-1.38	0.04	73.83	-0.02	-6.93	-0.01
Quickflow ('000 m3/year)	LULC 2001/02	1,576	877	611	4,599	643	413	8,746	31	3,542	5,090	109	278	8,836	150	3,503	4,792	41	60,167	2,631	106,635
	LULC 2018/19	1,386	967	689	7,996	542	117	7,021	36	3,542	4,980	99	278	7,738	132	3,423	4,802	66	60,149	2,420	106,381
	Change in quickflow (2018/19 less 2001/02)	-191	91	77	3,397	-101	-296	-1,725	5	0	-110	-9	0	-1,098	-18	-80	9	25	-18	-211	-253
	% change = [Change ÷ (2001/02)] X 100%	-12.11	10.34	12.64	73.85	-15.68	-71.71	-19.72	15.41	0.00	-2.16	-8.71	0.00	-12.43	-12.04	-2.27	0.19	61.20	-0.03	-8.02	-0.24
Local recharge ('000 m3/year)	LULC 2001/02	15,724	7,059	5,534	37,543	305	5,354	118,798	211	15,817	90,642	483	42	89,617	626	33,014	8,837	145	-5,656	-1,461	422,634
	LULC 2018/19	15,703	8,176	6,827	71,400	262	1,489	100,103	256	15,817	89,662	442	42	76,526	630	32,605	8,834	255	-5,689	-1,276	422,061
	Change in local recharge (2018/19 less 2001/02)	-21	1,116	1,293	33,857	-43	-3,865	-18,695	44	0	-979	-41	0	-13,092	4	-409	-4	110	-33	185	-573
	% change = [Change ÷ (2001/02)] X 100%	-0.13	15.81	23.37	90.18	-14.16	-72.19	-15.74	20.90	0.00	-1.08	-8.51	0.00	-14.61	0.63	-1.24	-0.04	75.77	0.58	-12.64	-0.14
Baseflow ('000 m3/year)	LULC 2001/02	16,471	7,223	5,830	39,878	630	5,536	123,226	228	15,956	92,373	491	42	93,428	679	34,206	9,031	157	14	0	445,399
	LULC 2018/19	16,350	8,358	7,119	75,510	535	1,539	103,609	276	15,956	91,343	449	42	79,883	681	33,763	9,030	275	14	0	444,732
	Change in baseflow (2018/19 less 2001/02)	-122	1,135	1,288	35,632	-96	-3,997	-19,617	48	0	-1,029	-42	0	-13,545	2	-444	-0	119	-0	-0	-667
	% change = [Change ÷ (2001/02)] X 100%	-0.74	15.71	22.10	89.35	-15.18	-72.20	-15.92	21.10	0.00	-1.11	-8.59	0.00	-14.50	0.25	-1.30	-0.00	75.74	-0.30	-0.88	-0.15

Appendix F

Flow diagram of the freshwater ecosystem services assessment framework developed and applied for this study