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A coupled modeling approach to assess the effect of forest policies in water provision: A biophysical evaluation of a drought-prone rural catchment in south-central Chile

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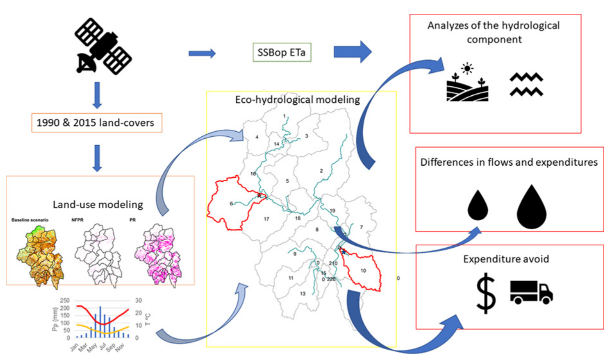
HIGHLIGHTS

- A Dyna CLUE model was used to define different forest policy scenarios.
- A SWAT model evaluated the impact of policy scenarios on water provision.
- An early Native Forest Law could have given a larger area of native forest.
- A policy oriented to small and medium landowners might have increased ows.
- A timely policy implementation could have saved spending in water trucks (2017–2018).

GRAPHICAL ABSTRACT



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ABSTRACT

The effect of different forest conservation policies on water provision has been poorly investigated due to a lack of an integrative methodological framework that enables its quantification. We developed a method for assessing the effects of forest conservation policies on water provision for rural inhabitants, based on a land-use model coupled with an eco-hydrological model. We used as a case study the Lumaco catchment, Chile, a territory dominated by native forests (NF) and non-native tree farms, with an extended dry period where nearly 12,600 people of rural communities get drinking water through water trucks. We analyzed three land-use policy scenarios: i) a baseline scenario based on historical land-cover maps; ii) a NF Recovery and Protection (NFRP) scenario, based on an earlier implementation of the first NF Recovery and Forestry Development bill; and iii) a Pristine (PR) scenario, based on potential vegetation belts; the latter two based on Dyna CLUE, and simulated between 1990 and 2015. Impacts on water provision from each scenario were computed with SWAT. The NFRP scenario resulted in an increase of 6974 ha of NF regarding the baseline situation, and the PR scenario showed an increase of 26,939 ha of NF. Despite large differences in NF areas, slight increases in inflows (Q) were found between the NFRP and the PR scenarios, with relative differences with respect to the baseline of 0.3% and 2.5% for NFRP and PR, respectively. Notwithstanding, these small differences in the NFRP scenario, they become larger if we analyze the cumulative values during the dry season only (December, January, and

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February), where they reach 1.1% in a normal year and 3.1% in a dry year. Flows increases were transformed into water truck costs resulting in up to 441,876 USD (monthly) of fiscal spending that could be avoided during a dry period.

1. Introduction

Human activity has become the major driver of global environmental change (Lewis and Maslin, 2015; Stocker et al., 2011). In particular, land-use change has led to land degradation and desertification, the alteration of carbon and nitrogen fluxes, biodiversity loss, soil erosion, and changes in the water cycle (Steffen et al., 2015; Wolff et al., 2018). Land-use change, like the afforestation with non-native species, affects hydrological processes such as evapotranspiration (Dias et al., 2015; Li et al., 2017), water yield (Bosch and Hewlett, 1982; Lara et al., 2009; Little et al., 2015), sediment and nutrient transport (Birkinshaw et al., 2011; Oyarzun et al., 2007), and groundwater recharge (Friesen et al., 2018). These hydrological alterations can be heightened by changes on air temperature and precipitation patterns due to global climate change (Galleguillos et al., 2021; Serpa et al., 2015; González et al., 2020).

For central Chile, the last decade was one of the warmest in the last 100 years; it also underwent an ongoing drought that stands out as the most extended dry period ever recorded in Chile (Garreaud et al., 2020). This megadrought is causing higher evaporation rates from open areas, greater evapotranspiration (ET) from crops and natural vegetation, and accelerated snow melting (Garreaud et al., 2017). It also led to a significant reduction in river flows, and acute scarcity of drinking water for rural communities whose main sources is the Rural Drinking Water System (RDWS or APR for “Agua Potable Rural” in Spanish) (Alvarez-Garreton et al., 2018; Garreaud et al., 2017; OCDE, 2016). To cope with local water shortage, the response of the central government has been to increase the national budget allocated for water supply to rural inhabitants. Between 2010 and 2020, the Chilean State has paid nearly USD 306 million (AMEOANNA, 2020) for the delivery of drinking water through water trucks to rural people (nearly 500,000 inh., (DGA, 2016)).

The climate has changed, and so has land-use in central Chile. In the early 1970s, socioeconomic transformations enforced in Chile by the military dictatorship propelled an economic model that favored a forestry industry based on non-native tree farms (Cubbage et al., 2007; Niklitschek, 2007). Due to the lack of land-use regulations, high profitability and government subsidies, such as the Decree Law 701, tree farms expanded rapidly at the expense of shrubs, degraded lands, and native forests (Heilmayr et al., 2020). By 1973, Chile had approximately 330,000 ha of tree farms (Armesto et al., 2010; Camus, 2006), which increased up to nearly 2.3 million ha by 2018 (INFOR, 2019). During the 1990s there were some regulatory attempts to promote the maintenance of the native forest, through the Native Forest Recovery and Forestry Development bill (Bulletin N°669-01, 1992). However, and only after 16-years of discussion, in 2008, the Chilean Congress approved a Native Forest Recovery and Forestry Development law (Law 20,283 of 2008) with fewer restrictions and spatial regulations than the original bill. The original bill had 19 articles enforcing the protection of native forest, while the final law had only 9 articles, offering less protection for the native forest (Armesto et al., 2010; Arnold, 2003; Biblioteca del Congreso Nacional de Chile, 2018; Manuschevich, 2016, 2018; Manuschevich and Beier, 2016). To illustrate, the original bill of law 20,283 considered a fine of 670 to 6700 USD per hectare for cutting tree species considered vulnerable or rare, which was reduced to a 335 to 3350 USD in the approved law (Biblioteca del Congreso Nacional de Chile, 2018). The weak regulatory content of the final Native Forest Recovery and Forestry Development law can be explained by an extreme interpretation of property rights, where judicial and congressional power favored the private right and forest ownership over the social benefits provided by native forests (Manuschevich, 2016, 2018). This argument continued for decades with the generic discourse of the foregone private gains of forest exploitation if mandatory conservation of native forest was in place, and the maintenance of fiscal discipline, i.e., restricted government expenditures (Manuschevich and Beier, 2016).

Today's global adaptation efforts have led to massive afforestation pledges by several developing countries. For example, the Bonn Challenge and the Trillion Trees Initiative, aim to address the intertwined challenges of rural poverty, climate change, and biodiversity loss through large-scale afforestation and reforestation. As of 2019, the area pledged globally to be planted with tree plantation was 100.2 Mha, which is equivalent to the entire area of Venezuela. Some countries, like Kenya and Uganda, pledged to increase their area planted with tree farms by 97.4% and 74.2%, respectively (Lewis et al., 2019). However, such massive endeavors must take into account all the potential side-effects derived from land-use change, such as the modification of the hydrological cycle and its consequent reduction of water availability to the population. It is very likely that such trade-offs are going to increase if massive afforestation policies are in place, particularly in water-limited regions. Under those conditions, an accurate quantification of water-related ecosystems services under different plausible land-use scenarios is, therefore, a key challenge to guarantee the sustainability as it is defined by the UN Sustainable Development Goals (United Nation, 2015), like the simultaneous reduction of poverty (SDG1), access to clean water and sanitation (SDG 6) and life on land (SDG 15). For this purpose, the coupling of Land-use and Land-cover Change (LULCC) scenarios and process-based models can be a valuable approach to better understand the impact of environmental policies on the land-cover and its changes, and to quantify their effects on ecosystem services (Manuschevich et al., 2019), such as those related with the hydrological cycle (Kim et al., 2019; Memarian et al., 2014).

In this study, we proposed a novel methodological approach that combines the Dynamic Conversion of Land-use and Its Effects model (Dyna CLUE) (Verburg and Overmars, 2009) with the Soil and Water Assessment Tool (SWAT) ecohydrological model (Arnold et al., 1998),widely used to determine eco-hydrological effects in forested areas (Yang and Zhang, 2016; Yang et al., 2018, 2019; Venkatesh et al., 2020; Carvalho-Santos et al., 2016). In particular, we evaluate whether an earlier implementation of the original Native Forest Recovery and Forestry Development bill would have resulted in a greater water provision for rural communities, and avoided an important fiscal expenditure in water truck provision. We tested our approach in Lumaco, a forest-dominated catchment in southern Chile (38°S), given its long-term history of land-use change and the severe impact of the ongoing megadrought. We tested the hypothesis that the timely implementation of the forest conservation policy would have reduced the current deficits of water provision in the poor rural areas of the Lumaco catchment. In this sense, our main objective was to assess how the early implementation of a native forest protection law would have impacted water supply today, especially for rural populations.

2. Materials and methods

2.1. Study area

The Lumaco catchment (Fig. 1) is located in the southern part of the Nahuelbuta mountain range, in the Araucania region (lat. -37.82° to -38.26°; lon. -73.21° to -72.80°). The Lumaco river tributes to the Imperial river, and has an area of 1026 km^2, and its elevation varies between 86 and 1448 m.a.s.l. Mean rainfall in the Lumaco Station is 1090 mm per year, while the mean air temperature is around 10 °C, corresponding to Temperate Climate of Dry and Warm Summer (Csb) according to the Köppen-Geiger climate classification (Beck et al., 2018). Hydrological flow, within 95% of the time, is not superior to 200 m^3/s with a main daily discharge of 15 m^3/s at the Lumaco flow station. As of 2015, the

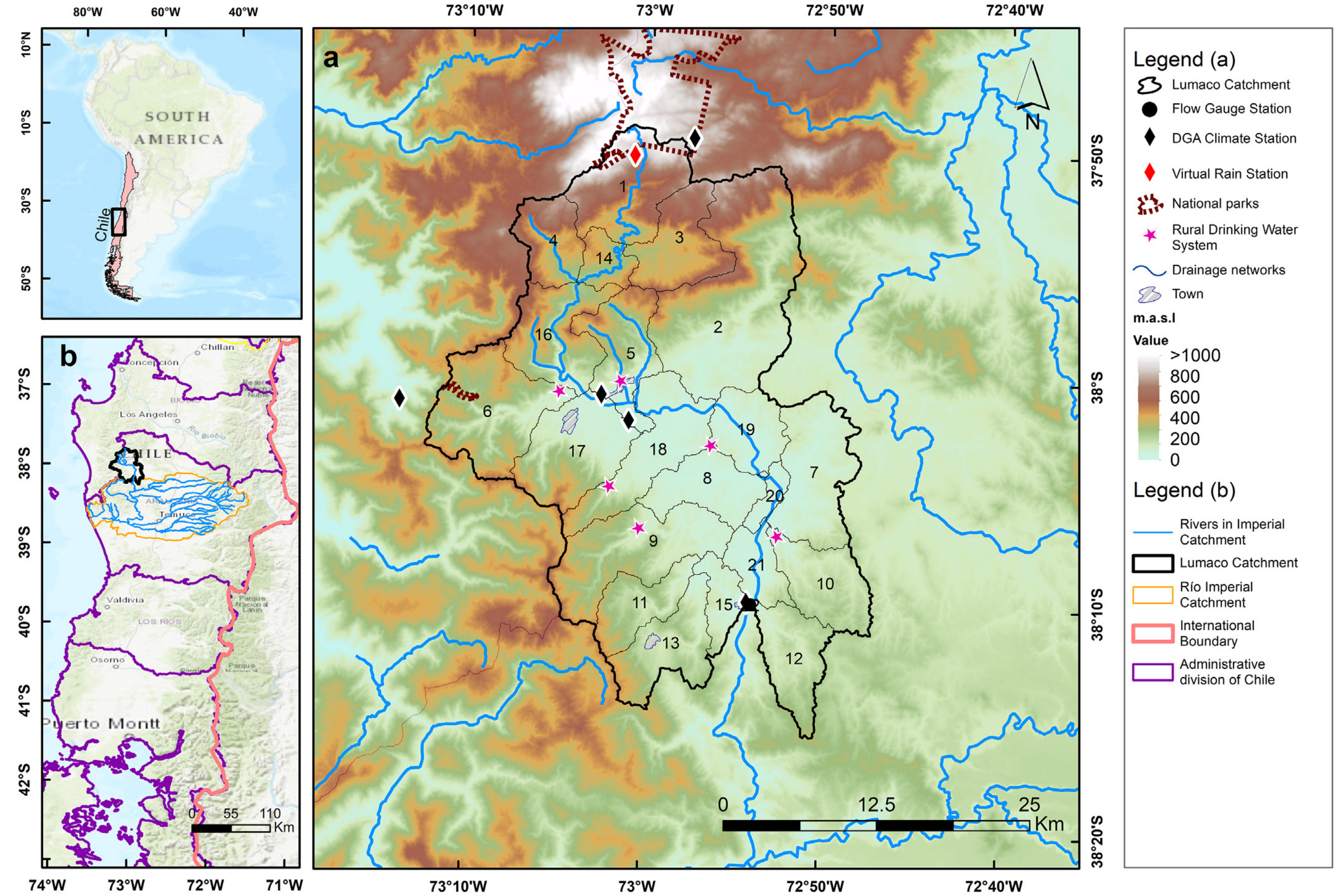

Fig. 1. Overview of the Lumaco river catchment. The meteorological and pluviometric stations, the towns inside the catchment and the location of the Rural Water committees (APR) are presented.

main land-covers were: forest shrubland and young forest (31%); industrial tree farms (26%) of *Pinus Radiata* and *Eucalyptus sp*; and native forest (24%), almost all of which are deciduous forests, dominated by *Nothofagus obliqua*. *Nothofagus obliqua* is, in some cases, associated with *Nothofagus dombeyi* and *Cryptocaria alba*, or *Nothofagus alpina*. At higher altitude, small patches of *Araucaria araucana* forests are present (Luebert and Pliscoff, 2018) within the Nahuelbuta National Park that covers 10% of the catchment. The main economic activity is related to the forest industry and trade (Ilustre Municipalidad de Purén, 2017; Ilustre Municipalidad de Lumaco, 2014), and the rural population is nearly 12,600 people (INE, 2017).

The catchment provides ideal conditions to study the effect of land-use on different components of the hydrological cycle for three reasons: i) irrigation can be neglected, since the anthropogenic activities are mainly rain-fed crops or tree farms; ii) it has little hydraulic infrastructure, such as irrigation channels and reservoirs; and iii) it has a mosaic of native forest and tree farms, due to the implementation of forestry policy. Six Rural Drinking Water Systems (RDWS) are located within the catchment, providing water to 14% of the catchment population, i.e., nearly 3500 users (DGA, 2014).

2.2. Data sources

2.2.1. Topography and soils

We used the 12.5 m TanDem-X Digital Elevation Model of the German Aerospace Center and EADS Astrium. The soils of Lumaco are classified as Inceptisol, based on the Chilean official soil information for the Araucania region (CIREN, 2002). The cartographic data was created from agrological studies according to the technical standards of the Soil Survey Manual (Soil Science Division Staff, 2017). Soil information is available in vector format and provides background information on a modal profile based on the morphological (colour, stains, structure, weathering and depth), physical (texture, density, humidity), chemical (pH, electrical conductivity, base saturation) and biological (organic matter, organic carbon) properties of the soil, together with a FAO taxonomic classification at a scale of 1:20,000 (CIREN, 2002). We converted all data-sets to a 30 m raster at for incorporation into the hydrological model. We also obtained 11 different textural classes and soil depths from the agrological studies database. Soil depth was fixed to 3 m for tree covers such as tree farms and native forest according to their capabilities to extract water from deeper horizons (Sands and Nambiar, 1984; Teskey and Sheriff, 1996). We have increased the Soil Available Water Content value to 20% for the entire catchment, since this modification provided better simulation according to adjustments with satellite summer ETa and simulated summer flows.

2.2.2. Land-cover data

Two land-covers with 30 m pixel resolution were used, one for 1990 and other for 2015. They were created through a supervised classification using Landsat TM image for 1990 and Landsat 8 for 2015 (Landsat product courtesy of the U.S. Geological Survey), based on the maximum likelihood method. Several spectral and topographic predictors were obtained from the Landsat reflectance products, following the methodology implemented in Zhao et al. (2016). The classifications were verified using Landsat 5 and 8 spectral information and Google Earth high-resolution imagery. For 2015, we used high-resolution Google Earth imagery and expert knowledge to select 300 training and 488 validation points. To control a correct designation of the land cover classes identified with the medium resolution Landsat imagery of 1990, we selected 100 training and 320 validation points among

Table 1
Real land-cover features in Lumaco catchment.

Land-cover	SWAT Land	SWAT Code	1990 (ha)	1990 (%)	2015 (ha)	2015 (%)
Bareland	Barren	BARR	19,678.1	19.2	11,210.7	10.9
Agriculture	Agricultural Land-Generic	AGRL	9819.2	9.6	5303.0	5.2
Grassland	Pasture	PAST	3130.8	3.1	3094.1	30
Shrubland and young tree farms	Range-Brush	RNGB	33,582.0	32.7	31,821.4	31.0
Deciduous forest	Oak	OAK	22,919.1	22.3	21,625.0	21.1
Evergreen forest	Forest-Evergreen	FRSE	3190	3.1	2633.1	2.6
Tree farms	Forest-Evergreen	EUCA	10,307.1	10.0	26,939.0	26.2
Water body	Water	WATR	15.6	0.0	15.6	0.0
Total				102,641.8	102,641.8	

the one selected for 2015 and checked that the spectral signature derived from Landsat satellites was the same between 1990 and 2015 to confirm the reliability of the points used in the 1990 classification. Kappa coefficient for the 1990s land-cover was 0.81, while for the land-cover of 2015 it was 0.84, with an overall precision of 84.7% and 87.7%, respectively. A logic decision rule procedure was implemented to correct possible inconsistencies in the 1990 land-cover map. The procedure defines that pixels classified as"Tree farms" or"Agriculture" in 1990, but corresponding to a native forest category (Evergreen or Deciduous) in 2015, were reclassified as the latter native forest category. Similarly pixels classified as"Bareland" or"Agriculture" in 1990, but corresponding to shrubland and young plantation category in 2015, were modified to the latter category. We applied these criteria due to the implausibility that these changes occur under the conditions and incentives of that period. A 3 × 3 majority filter was applied for both land-cover periods, allocating isolated and anomalous pixels to obtain a sharper spatial distribution of the categories. The different land-cover categories were adapted to the hydrological model nomenclature and the resulting categories are depicted in Table 1.

2.2.3. Climate data

Daily precipitation and air temperature data were obtained from three weather stations from the Chilean Water Resources Institution (DGA) for the 2000–2018 period (Supplementary Table 1). Data gaps were filled in with the daily and 5-km resolution CR2MET precipitation and temperature dataset, available from the Center for Climate and Resilience Research server (http://www.cr2.cl/datosproductos-grillados). Quality assessment of the precipitation data was performed using a mass curve analysis (Dingman, 2015). A virtual rain gauge was included to represent the topographic effect, as previously reported for Chilean coastal range (Garreaud et al., 2016). We used a virtual rain gauge to represent rainfall at high elevations, using data from the daily 5-km resolution CR2MET precipitation dataset (http://www.cr2.cl/datos-productos-grillados).

2.3. Modeling the alternative land-use scenario

To obtain the LULCC scenario based on Native Forest Recovery and Forestry Development bill, we used the Dynamic Conversion of Land-Use and its Effects, Dyna CLUE model (Verburg and Overmars, 2009). Firstly, we selected the 1990 and 2015 land-cover, and masked classes covering less than 2% of the total study area (e.g., water). Secondly, we established the land demand, which represents the area assigned to each land class for each time step (Manuschevich and Beier, 2016; Verburg and Overmars, 2009). To establish the basis for the simulation, we estimated land-cover demand by calculating the average yearly change and applied a linear extrapolation trend to estimate the demand for land for each land-cover type for each year during the simulation period (1990–2015). Third, we provided conversion rules that include spatial restrictions in the conversion matrix. We estimated the conversion elasticity for each land-cover type and created a transition matrix for Dyna CLUE. The conversion elasticity, which is the stability of a land-cover type, was derived from the analysis of land-cover change from 1990 to 2015. In building the transition matrix, it is necessary to set up specific transition rules by indicating which conversions are allowed or disallowed, as well as how much time the transition will require. We developed our transition matrix based on a policy analysis of legislative and regulatory documents, literature review and expert criteria (Supplementary Table 2). Fourth, Dyna CLUE requires estimates of spatial factors (or predictors) that may influence land-cover transitions. In our research, 12 predictors were used for the different models (Supplementary Table 3). Candidate predictors were selected according to a bibliographic revision of other studies where Dyna Clue was used (Manuschevich and Beier, 2016; Lima et al., 2011). To establish the main factor for each land-cover type, we conducted 7 regressions, one per land-use without considering the water bodies. The results of logistic regressions are evaluated with the Receiver Operating Characteristic (ROC) method, where the area above the curve shows the precision, with values close to 0.5 and 1 representing a random model and a close-to-perfect model, respectively (Dodd and Pepe, 2003) (see result in Supplementary Fig. 1).

We ran the basic Dyna CLUE model for calibration and verification, and then used the calibrated model to simulate the policy scenario. The validity of the basic model was compared to the 2015 land-cover map using the kappa coefficient and kappa simulation coefficient (Cohen, 1960; van Vliet et al., 2011). We also used a fuzzy kappa simulation to restrict the analysis to covers that are susceptible to be confused (van Vliet et al., 2011, 2016). Finally, to evaluate the impact of land-use changes on the hydrological processes of the watershed, we assembled a Native Forest Recovery and Protection Scenario (NFRP) based on an earlier version of the Native Forest Recovery and Forestry Development bill, as if it would have been implemented in 1990 (Bulletin N° 669) (Biblioteca del Congreso Nacional de Chile, 2018), and established two additional scenarios: one baseline scenario based on a basic Dyna CLUE simulation model (2015), to compare the different hydrological conditions of the Lumaco river catchment to the other land scenarios; and a Pristine Scenario (PR), considering the natural condition in the Lumaco catchment. The characteristics of land-cover demands in each scenario are specified in Table 2.

2.4. Hydrological modeling

SWAT is a process-based, catchment-scale semi-distributed hydrological model which uses hydrological response units (HRU) to represent water fluxes within the catchment. HRUs are homogeneous areas in terms of soil type, land-cover, slope, and water management (Neitsch et al., 2005), which allows a detailed evaluation of the components of the water balance for different land-covers (Arnold et al., 2012). The surface runoff is estimated in SWAT with the modified "SCS curve number" method. SWAT uses the variable storage routing method to calculate water movement through the main drainage network, while potential ET was computed with the Hargreaves formula based on data availability. For further details of the equations involved in the processes, see the theoretical documentation of the model in (Neitsch et al., 2011). The QGIS software was used as an interface (Dile et al., 2015) to prepare the input data used to run SWAT 2012 rev.637.

First, we determined 206 Hydrological Response Units (HRUs), identifying 46 HRUs of tree farms and 26 of native forest. We selected 2000–2018 as the simulation period to be consistent with the land-cover change dynamic of the catchment. The 2015 land-cover was considered to be representative of this period. To reduce the number of parameters

Table 2
Main characteristics LULCC scenarios.

Name	Description
Baseline scenario	The basic simulation scenario on Dyna CLUE based on land-cover 2015. This scenario serves as a baseline to contrast the hydrological effects of the other two LULCC scenarios. Changes during the 1990–2015 period were promoted by tree farms subsidies, in particular the DL701 implemented in 1974, and by the most recent native forest protection regulation implemented with the Law 20,283 in 2008. The demand and transition matrix for Dyna CLUE are based on analysis of 1990 and 2015 land-covers.
Native Forest Recovery and Protection Scenario (NFRP)	Based on the original bill for recovery of the native forest presented in April 1992 (Biblioteca del Congreso Nacional, 2018). This original bill had restrictions to land-use changes in areas covered with native forest (Art. 24), and incorporated a monetary incentive to small owners if they reforested with native species (Art. 11). We translated this policy into a demand for land areas, assuming that all small owners (> 150 ha) would switch from tree farms to native forests. Also, we restricted the changes in Native Forest of 1990 in the transition matrix.
Pristine Scenario (PR)	All tree farms are replaced with native forest according to the potential native vegetation belt defined by Luebert and Pliscoff (2018). The aim of this scenario was to quantify hydrological processes under the biophysical limits of the system in order to compare the hypothetical water production in a catchment without the intervention of the forestry industry.

to be calibrated, we performed a sensitivity analysis of 18 parameters, based on literature review. This analysis was carried out using the Latin Hypercube One factor At a Time (LHOAT) algorithm (van Griensven et al., 2006) implemented in the hydroPSO R package (Zambrano-Bigiarini et al., 2013). Parameters were selected to represent the following processes: runoff (CN2, CNCOEF, SURLAG and OV N); infiltration/percolation (GW DELAY, GWHT, RCHRG DP, GWQMN, ALPHA BF, SHALLST, GW REVAP, GW SPYLD, and REVAPMN); evapotranspiration (EPCO, CANMX, and ESCO); and water routing (CH N (2) and CH K (2)) (Supplementary Table 4). Variation ranges were obtained from the SWAT manual (Arnold et al., 2012; Neitsch et al., 2011). The parameters describing the management and phenological cycle of tree farms (EUCA) were modified based on previous works in similar local conditions (Crockford and Richardson, 1990; Forrester et al., 2010a, 2010b).

We processed the calibration with the hydroPSO global optimization algorithm (Zambrano-Bigiarini et al., 2013), using the Nash-Sutcliffe goodness-of-fit index (NSE) (Nash and Sutcliffe, 1970) as the objective function and the default PSO configuration described in Zambrano-Bigiarini et al. (2013). The parameter values are defined by default on the SWAT model according to soil, topography and land use. We used the specific range defined for those parameters obtained from the SWAT manual to initialize the calibration. The warming up, calibration and verification periods ranged from 2000 to 2002, 2003 to 2011, and 2012 to 2018, respectively. The model was run on a monthly time scale.

Results of the LH-OAT sensitivity analysis led to calibrate only 10 of the 18 analyzed parameters (Supplementary Table 4). The most significant parameter was the curve number (CN2) used for each of the three land-covers analyzed: tree farms, native forest, and shrubland. Parameter values obtained with the hydroPSO algorithm are shown in Supplementary Fig. 2.

We evaluated the performance of model simulations using three different indices: the NSE, the percentage of bias (PBIAS), and the ratio between the mean square error and the standard deviation of the data (RSR). In general, simulations of hydrological models for average monthly flows are considered satisfactory, if they satisfy: NSE $\geq$ 0.50, RSR $\leq$ 0.70, and PBIAS = 25% (Moriasi et al., 2015).

In addition, we included a comparison at a monthly scale of the ETa simulation obtained by SWAT against a Satellite ETa product obtained from the SSEBop Evapotranspiration Products, which is based on the solving of the energy balance, using land surface temperature based on satellite data and globally available meteorological data (Senay, 2018) . We analyzed the 2003–2018 period at monthly scale (according to the product availability), then we considered only dry season months, where vegetation maximize their water use. The SSEBop product was chosen since it has been reported to have accurate estimation of ETa in pastures of southern Chile (Moletto-Lobos et al., 2020).

2.5. Hydrological response of LULCC scenarios

To evaluate the effect of the hydrological response of different land-covers on flows, the two previously defined LULCC scenarios (NFPR and PR) were compared against the baseline scenario in terms of the relative change (%) in monthly flows at yearly and seasonal scale, considering the 2002–2018 period. SWAT flow values were calculated at the catchment and sub-catchment scales. SWAT allows to obtain flow values at both catchment and sub-catchment scales, which allowed us to analyze the flow values at the catchment in two scales: the whole Lumaco catchment (1026 km^2) and the Boyeco (76 km^2) and the Hueico (43 km^2) subcatchments, each with a RDWS near to the sub-catchments outlet. Moreover, in both cases, the different hydrological responses were analyzed on a seasonal scale, in order to determine whether these may be greater, especially in the dry season (summer).

In addition, a detailed evaluation of changes in actual evapotranspiration (ETa) and Water Yield (WY) was done through monthly box-plots at the HRU scale. The year 2015 was selected to analyze these spatio-temporal patterns, since it had a nearly normal annual precipitation during the megadrought (1090 mm), corresponding to the year of the present land-cover map used.

2.6. A biophysical assessment and provision of drinking water for rural inhabitants

The drinking water by water trucks was obtained through a search of public bids made through the Mercado Público system in 2017 for the Araucanía region (Mercado Publico, 2017) and a transparency request to the national emergency office (ONEMI) in 2017 (Officio N° 48/2017, ONEMI). First, we analyzed the tendering of water trucks supply (Mercado Publico, 2017) in the Araucanía's districts and the monthly average costs associated with their operation [USD/month/truck] for each administrative district in the catchment, which was nearly USD 3500. Approximately, 12 water trucks would be operating per month within the catchment's districts in 2017. We multiplied the number of trucks with the mean cost of water truck operation to obtain the monthly average cost. We assumed that the water truck operation in each district is entirely operated within the catchment boundaries. Also, we assumed an average volume of 10 m^3 per water truck, since no information about the volume of water supplied by each of the twelve trucks was available. Then, we compared the volume of water delivered by trucks with the difference in the monthly flow volumes resulting from the simulation of the NFRP and PR scenarios.

2.7. Workflow and analysis framework

The general framework of the proposed methodology is presented in Fig. 2, where we can distinguish five main steps: i) generation of land-use scenarios with details about the Dyna CLUE model implementation (beige frame); ii) SWAT model implementation (yellow frame), with a general description of the hydrological modeling calibration and verification procedure; iii) simulated ETa assessment against satellite observations (green frame); iv) analysis of flow changes between the baseline scenario and the two LULCC scenarios (blue frame); v) estimation of the avoided expenditure due to the implementation of original bill of the Law 20,283 (red frame).

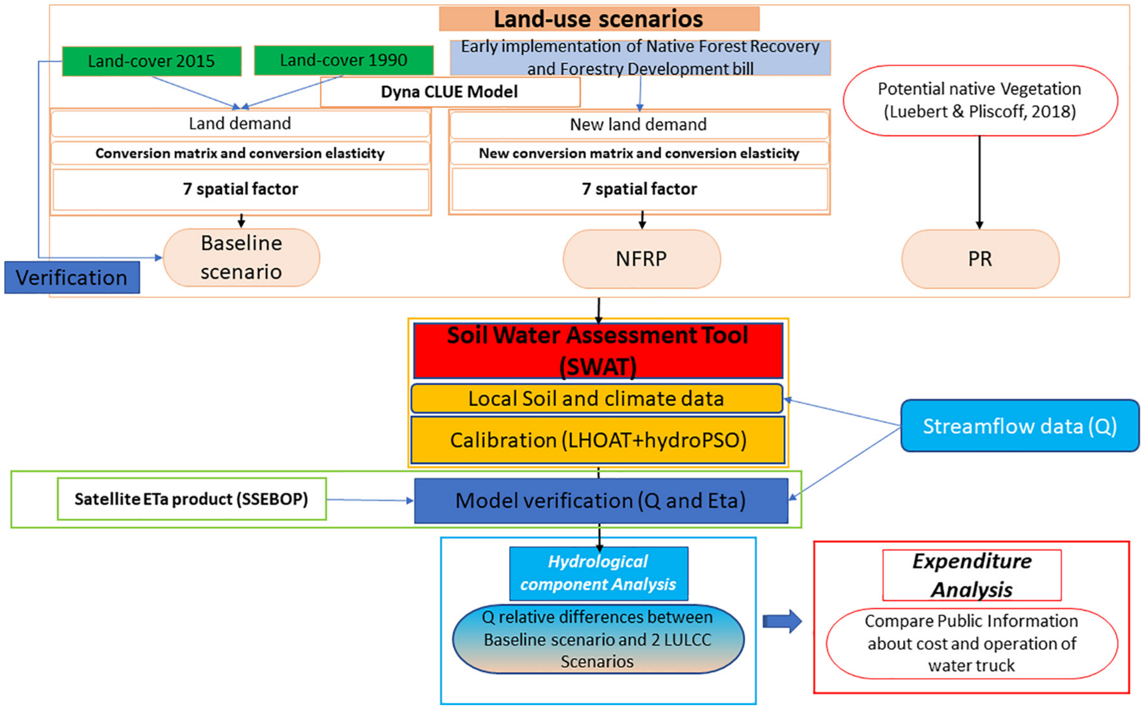

Fig. 2. Methodological scheme of assessment of LULCC policy impacts on catchment flows.

3. Results

3.1. Modeling the alternative land-use scenario

We have chosen the different land-use predictors for the final logistic regression (Supplementary Table 2) based on the results of the stepwise forward with Akaike Information Criterion for each land-use class. After this, we compared the basic land-use simulation of Dyna CLUE for 2015 with the 2015's land-cover and this had an overall agreement of 77% with a kappa coefficient of 0.703; the kappa simulation coefficient was 0.7, while the simulated fuzzy kappa reached a final value of 0.27, similar to previous works (van Vliet et al., 2011, 2016). Accuracy was poorest for the plantation class (kappa simulation of 0.52). This is because the basic simulation does not predict the clear cut and re-plantation cycle, which implies the confusion between shrub and young plantations in 1990.

For the study area, we did not observe a large difference between the simulated NFRP scenario and the baseline scenario (Fig. 3). Restrictions on land-use change (transition rules) meant an increase of deciduous native

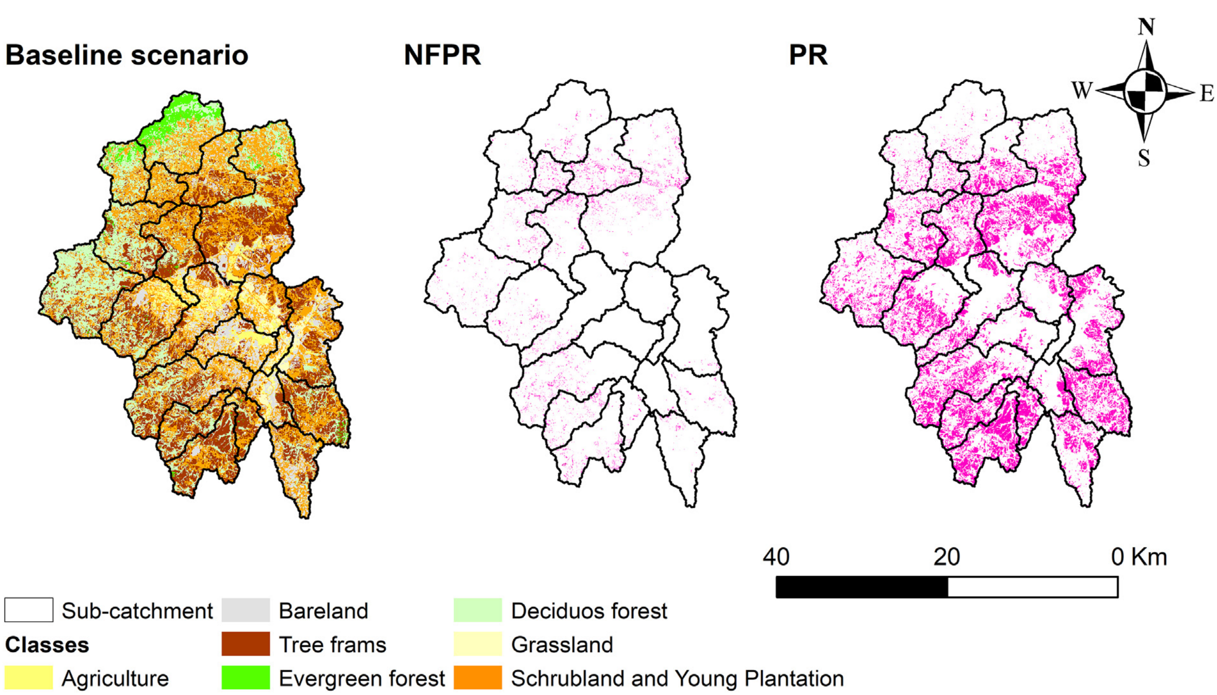

Fig. 3. Land-use change in different scenarios: Baseline scenario; Native Forest Recovery and Protection scenario (NFRP); and Pristine scenario (PR). The purple colour represents the changed areas.

Table 3
Dyna CLUE's simulation results.

Land-cover	Baseline		NFRP		PR	
	ha	%	ha	%	ha	%
Bareland	10,181.7	9.9	9437.9	9.2	10,181.7	9.9%
Agriculture	5856.5	5.7	6497.4	6.3	5856.5	5.7
Grassland	3110.6	3.0	3105.5	3.0	3110.6	3.0
Shrubland and young tree farms	32,354.9	31.5	31,117.3	30.3	32,354.9	31.5
Deciduous forest	23,059.9	22.5	26,014.1	25.3	47,979.3	46.7
Evergreen forest	3143.3	3.1	3213.6	3.1	3143.3	3.1
Tree farms	24,919.4	24.3	23,240.3	22.6	0	0
Water body	15.6	0.02	15.6	0.02	15.6	0.02
Total	102,641.8		102,641.8		102,641.8	

forest from 23,269 ha to 26,206 ha (+12%), while the tree farms decreased from 23,552 ha to 22,889 ha (−2%). We found that the shrubland class decreased from 33,424 ha to 31,495 ha (−5%). The most important change, in relative terms, was a decrease in grassland class from 3104 ha to 1855 ha (−40%). In the PR scenario, the 23,552 ha of tree farms was replaced by deciduous native forest (−100%) (Table 3).

3.2. Hydrological modeling performance

Monthly Nash-Sutcliffe efficiencies obtained during calibration (2003−2011) and verification (2012–2018) were 0.88 and 0.80, respectively, while the PBIAS and RSR were below 4% and 0.34, respectively (Fig. 4). The PBIAS and RSR in calibration time were below 4% and 0.34, respectively. These metrics are considered"Very good" for NSE and PBIAS and"Good" in the calibration and verification period (Moriasi et al., 2007). Therefore, we considered our results as an adequate representation of the hydrological processes occurring within the Lumaco catchment (Table 4).

The comparison of satellite ETa and the SWAT derived ETa was acceptable at a monthly scale with a NSE of 0.52, a PBIAS of −11.55 and a RSR of 0.70 (Table 4). The yearly water balance at catchment scale showed a very significant agreement from the two sources.

Table 4
SWAT Calibration and Verification simulation results against observed flow and verification against ETa observations.

Flow (Q)					
Calibration (2002 − 2010)			Verification (2011–2018)		
NSE	PBIAS	RSR	NSE	PBIAS	RSR
0.88	−1.1	0.34	0.80	−6.1	0.45
Evapotranspiration flow					
NSE	PBIAS	RSR	NSE	PBIAS	RSR
0.61	−14.61	0.63	0.43	−8.61	0.76

When comparing the annual ETa values for SSEBop along with the simulated ETa values from SWAT we see that the R^2 reaches a value of 0.3 (Supplementary Fig. 3). Yearly ETa simulated by SWAT systematically overestimated SSEBop observations, except for year 2016, where the opposite situation was observed, strongly affecting the correlation metrics (Fig. 5). However, when comparing monthly simulations considering only the dry period, we observed a better agreement ($R^2 = 0.59$) without bias. During the dry season we can observe important differences for low ETa values, where SWAT largely overestimated ETa from satellite information (Fig. 6).

3.3. Hydrological response of LULCC scenarios

The mean total yearly ETa for the complete period in tree farms HRUs was 731 mm, while Native Forest was 535 mm (Table 5). The ETa / P ratio was 0.7 and 0.5 in tree farms and native forest, respectively. The analysis of ETa at HRU scale showed an increasing trend from July to December (Fig. 7) in the native forest and tree farms land-uses, which is expected due to the natural development of the growing season of most vegetative species in the southern hemisphere. We also observed lower ETa for exotic tree farms during the summer months, while values for native forest showed some dispersion and decrease in the same period (Fig. 7a). Persistently, Native forest HRUs showed a higher amount of water yield even during dry or wet years (Table 5). Monthly dynamics show the same patterns, especially during winter months (JJA) where maximum Pp occurs (Fig. 7b).

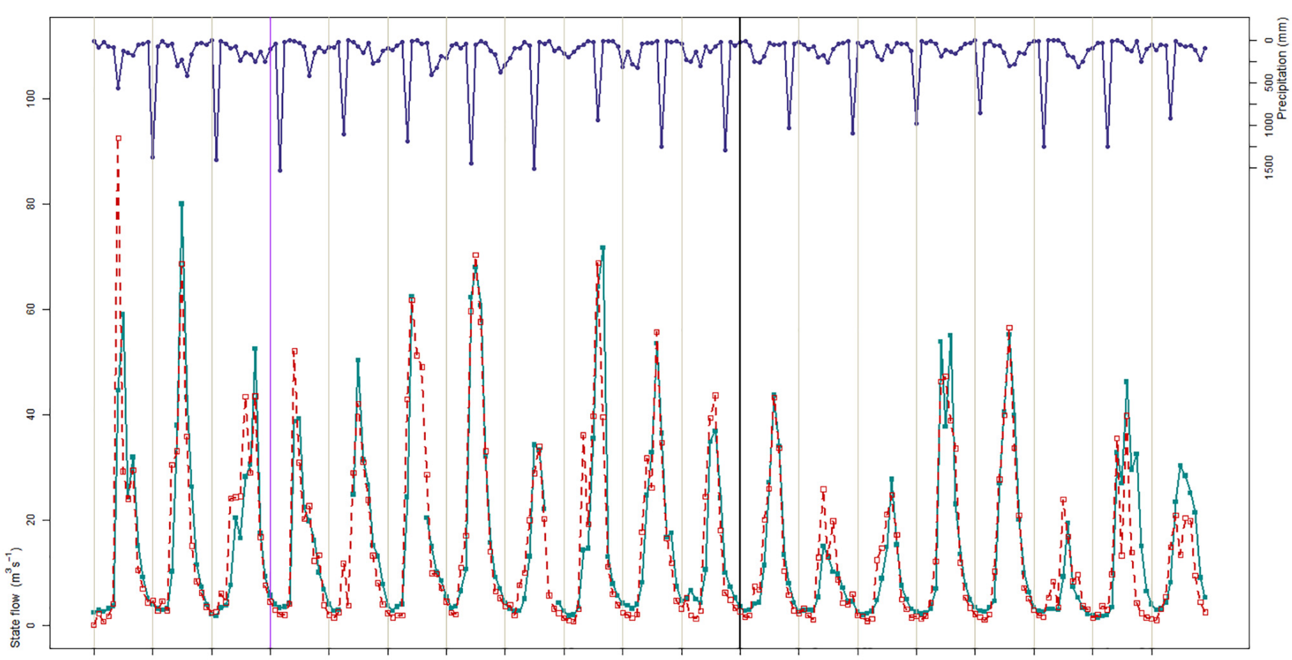

Fig. 4. Time series of monthly flows (Q) and rainfall. The light blue line represents the observed flow, the red dotted line represent the simulated flow and the blue lines represent the precipitation. The purple line represents the end of the warm-up period and the start of the calibration period while the vertical black line separates the calibration and verification periods.

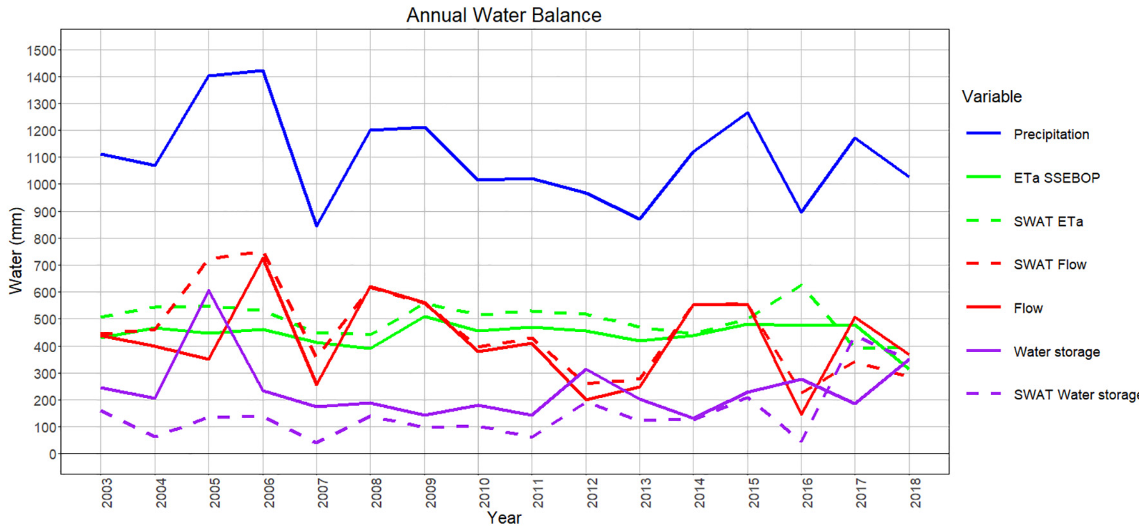

Fig. 5. Annual Water Balance comparison between local data and SWAT model simulation.

The analysis of flows under different LULCC scenarios showed an increase of 0.33 and 2.52% of mean annual flow expected for NFRP and PR scenarios, respectively. The increase is accentuated in summer months for NFRP scenarios with a mean increase of 0.50%, and a maximum value of 1.8% in 2008, while for the PR scenario, we observed a mean increase of 3.8%, with a maximum value of 13.9% in 2008 (Fig. 8). For the overall period (2002–2018, excluding the warm-up period), this is equivalent to annual water amounts of 0.49 and 3.50 m^3/s in NFRP and PR, respectively, or 1,262,277 and 8,204,801 m^3 water per year, respectively. Different flow responses are observed when considering the whole mega-drought period (2010 to 2018) as compared to the previous normal period (2002–2010), with a seasonal summer decrease of 0.68% instead of 0.42% for the NFRP scenario, and 4.94% instead of 3.47% for the PR scenario.

In sub-catchment 6, where a RDWS is located, (Boyeco, 7616 ha, Fig. 9), the NFRP and PR scenarios led to increases of 0.59 and 0.95% in the mean

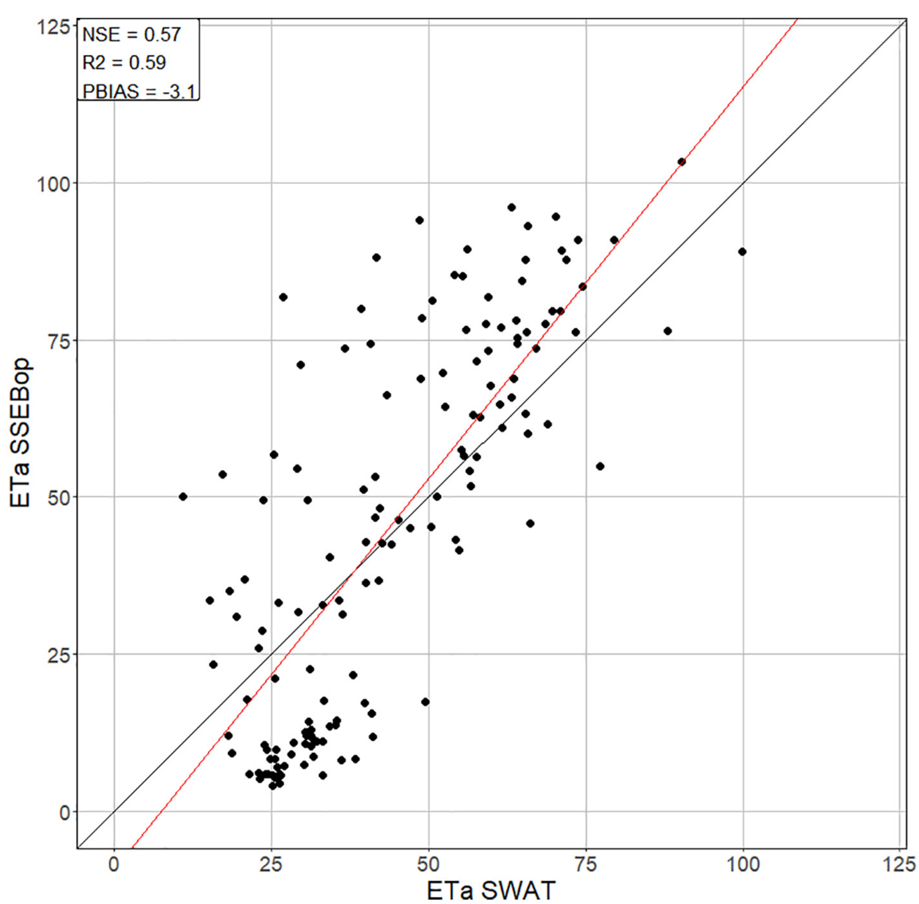

Fig. 6. Comparison between monthly ETa from SSEBop product and SWAT model simulation considering only dry seasons for the entire simulation period (2002–2018). The black line represents the perfect linear regression between variables and the red line represents the regression line obtained with the data for each variable.

Table 5
Mean, max and min values of ETa and WY in HRUs for tree farms and native forest.

	ETa (mm)		WY (mm)	
	Tree farms	Native forest	Tree farms	Native forest
Mean	731	535	297	439
Max	823	655	494	708
Min	611	452	143	212

annual and summer flows, respectively. The PR scenario led to larger increases of 2.09% in the mean annual values and 3.36% in summer flows. In sub-catchment 10 (Hueico, 4329 ha, Fig. 9) the NFRP and PR scenarios led to increases of 0.50 and 0.68% in mean annual and summer flows, respectively. The PR scenario led to larger increases, 3.54 and 4.56% in mean annual and summer flows, respectively.

We analyzed the relative differences in summer months for a normal year of precipitation and a dry year. The differences are lower in a normal summer period like 2015–2016, with a flow increase of 1.09% for the NFRP scenario and 7.61% for the PR scenario, while in 2011–2012 (a dry period) relative increase was of 3.10% for the NFRP Scenario and 21.17% for the PR Scenario (Table 6).

3.4. A biophysical assessment and provision of drinking water for rural inhabitants

As shown in Table 6, alternative scenarios would have resulted in more water for rural communities and less fiscal expenditure in water trucks. The NFRP Scenario in the Boyeco sub-catchment it would have provided a monthly average of 14,673 m^3 more water, while for the Hueico sub-catchment would have provided 4063 m^3 more water. These volumes are equivalent to 1467 and 406 water trucks operations of $10m^3$ capacity for Boyeco and Hueco sub-catchment, respectively (Supplementary Table 5).

Just in the Lumaco catchment, a rough first estimation of the monthly cost for the supply of drinking water through water trucks, is around 41,876 USD, which would mean an annual cost of 502,513 USD. The central government spends on an average 3490 USD per month in the operation of water trucks (Tender 1589–2-LE1) in the districts that compose the Lumaco catchment area. As of 2017, more than 12 trucks were operating in the catchment districts, distributing water daily for most of the year,

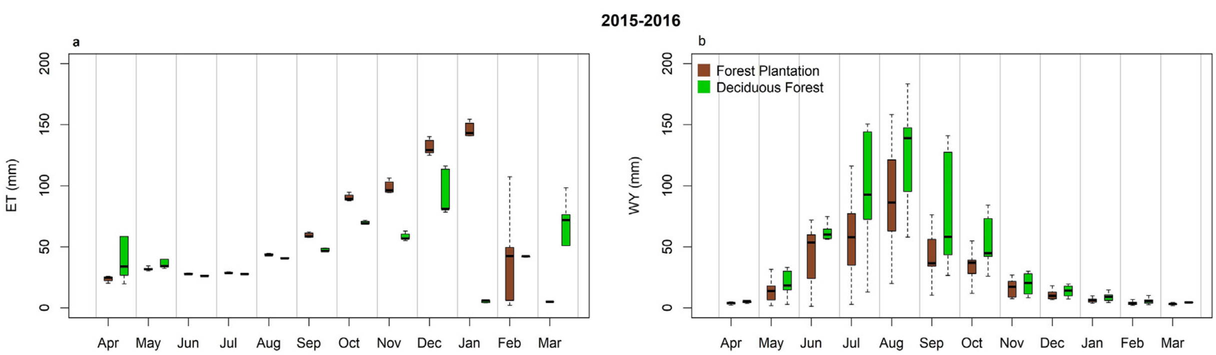

Fig. 7. Boxplots of the Tree farms and Deciduous native forest HRUs (46 and 26, respectively) for hydrologic year 2015–2016 in variables: (a) Actual Evapotranspiration (mm), and (b) Water Yield (mm).

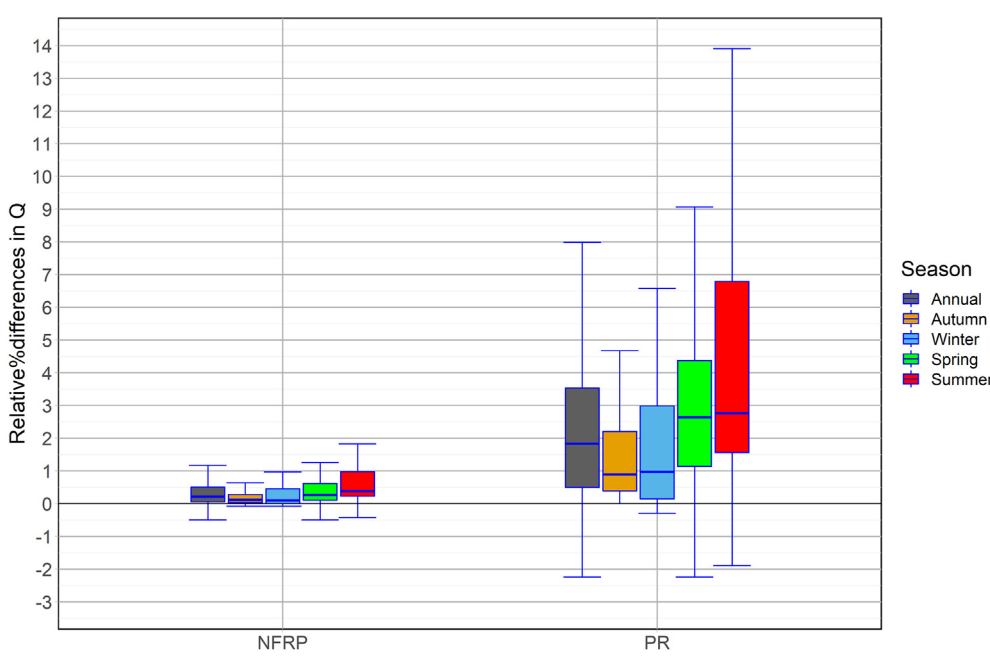

Fig. 8. Relative percentage changes in monthly flow rate with scenarios of land-use change / coverage at yearly (204 values for each month between 2002 and 2018) and seasonal (51 values per season) scale. NFRP: Native Forest Recovery and Protection Scenario; PR: Pristine Scenario.

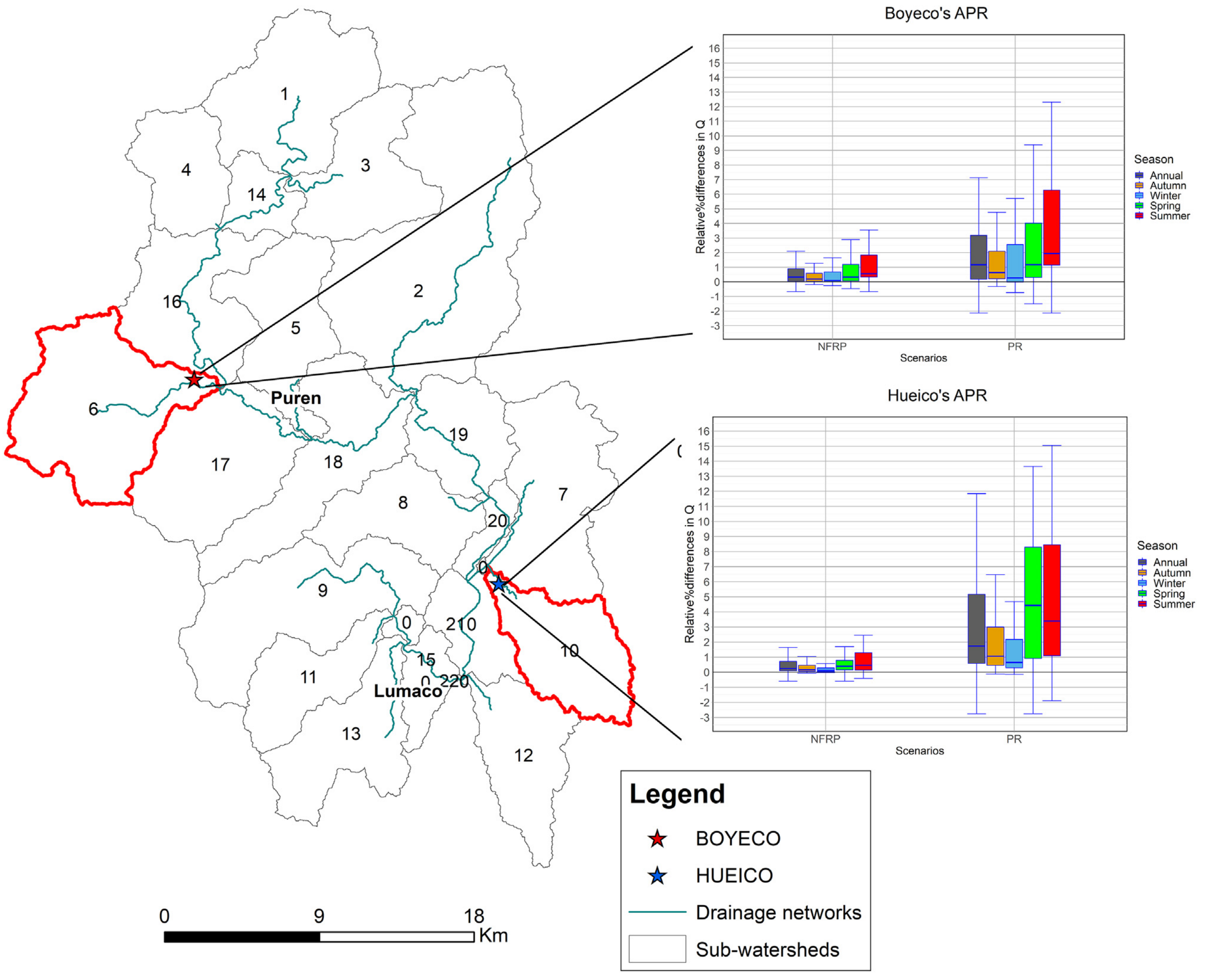

Fig. 9. Boyeco and Hueico RDWS and their relative percentage changes in monthly flow rate with scenarios of land-use change / coverage at yearly (204 values for each month between 2002 and 2018) and seasonal (51 values per season) scale.

which is equivalent to about 3600 m^3 of water (ONEMI's official letter 48/2017).

4. Discussion

We have provided an estimation of alternative regulatory and conservation scenarios and their impact on water provision, focusing on water for rural people. The methodology we developed can be important to comprehensively assess the hydrological impacts of the implementation of global initiatives such as the Bonn Challenge and the Trillion Tree Initiative, environmental and land-use management policy programs, as well as the United Nations Framework Convention on Climate Change with the REDD+ program, and the United Nations Convention to Combat Desertification (UNCCD, 2017). Griscom et al. (2017) estimated that, among all the natural climate solutions, reforestation can provide roughly a third Climate mitigation potential in 2030 (in terms of carbon storage and avoiding greenhouse gas emissions). However, those estimates depend on how and where those reforestation actions are conducted (Lewis et al., 2019). Massive afforestation/reforestation plans will likely increase in the future, which might have an impact over several SDGs and, therefore, integrative tools that take into account the combined effect of land-use and climate change are urgently needed.

Table 6
Comparison Q difference between a normal year versus a dry year in the Lumaco catchment.

Normal summer 2015–2016					
Scenario	Relative difference %	Q m^3	Q m^3/month	Trucks per month	Truck cost (USD)
NFRP	1.09%	0.04	103,680	345	1,181,950
PR	7.61%	0.25	648,000	2156	7,387,188
Dry summer 2011–2012					
Scenario	Relative difference %	Q m^3	Q m^3/month	Trucks per month	Truck cost (USD)
NFRP	3.10%	0.08	207,360	690	2,363,900
PR	21.17%	0.57	1,477,440	4916	16,842,788

4.1. Modeling performance and uncertainties

These results of land-cover change simulations performed with Dyna CLUE indicate a good representation of the model and align with the results of other research carried out in different continents (van Vliet et al., 2011; Manuschevich and Beier, 2016; van Vliet et al., 2016; Pindozzi et al., 2017; Romano et al., 2018). However, there are some points of land-cover modeling to consider that can introduce uncertainties. One of them is that models like Dyna CLUE have difficulties representing decision-making processes (Brown et al., 2013). To advance in this aspect, it is necessary to improve the spatial and temporal data used in the land-cover models, along with better integration of biogeophysical and socio-economic data into models, as well as improving the understanding of the dimensions of land-cover in terms of its function, cultural importance, density, management and value (Brown et al., 2013).

On the other hand, hydrological modeling results gave a reliable representation of the monthly flows at the catchment outlet, which could be considered as"very good" for NSE PBIAS and RSR in both periods (calibration and verification) (Moriasi et al., 2007). Zhang et al. (2016) obtained NSE values of 0.90 and 0.88 for calibration and verification of -monthly flows simulated with SWAT in the Heihe river catchment (China), while Stehr et al. (2010) obtained NSE values above 0.75 for monthly SWAT simulations in the Vergara river (southern Chile). It is worth noting the good NSE values obtained in our simulations, despite considering calibration (2002–2010) and verification (2011–2018) periods, were subject to very different hydrometeorological conditions, such as excess water due to the"El Niño" ENSO phenomenon of 2004–05 (Poblete et al., 2017) and the mega-dry phenomenon present since 2009 (Garreaud et al., 2017). The largest discrepancies between simulated flow and their corresponding observations occurred in wet periods, where there is an underestimation in the years with higher flow and an overestimation in the years with lower flow, possibly due to the uncertainty either in the input variables, precipitation or in the representation of the routing processes of the hydrological cycle. These results are consistent with other research, where problems have been observed in the simulation of flows in the SWAT model (Eckhardt and Arnold, 2001; van Liew et al., 2005; Rahman and Islam, 2020). An important point that can influence the uncertainty of the flow simulation is the presence of wetlands and flood areas within the catchment that are not represented in the land-cover of the year 2015. These would act as a sponge, retaining water in the wet period and mitigating the effect of precipitation on the flow rate (Bullock and Acreman, 2003). Besides, in the covers used, the differences between shrubs and young plantations were not distinguished because the working scale makes it difficult to differentiate them. This can influence the evapotranspiration and infiltration of important components within the water cycle in the system that is not being incorporated in the modeling (Khanal and Parajuli, 2014; Komatsu et al., 2011).

SSEBop has demonstrated good performance to estimate ETa in several contexts, such as different ecosystem around the United States of America (Chen et al., 2016; Senay, 2018; Velpuri et al., 2013) or in the Yellow river catchment in China (Yin et al., 2020), and including pastures of the south of Chile (Moletto-Lobos et al., 2020). However, at the catchment scale, the product has shown underestimation (Zhuang et al., 2021), which is consistent with our simulated ETa results that showed a good agreement with the SSEBop product but a slight systematic overestimation at the yearly scale. While the evapotranspiration simulation reached"adequate" for NSE,"good" for PBIAS and"satisfactory" for RSR in calibration periods, for the verification period, this simulation was"unsatisfactory" for NSE and RSR and very good for PBIAS (Moriasi et al., 2007). Regarding our research objectives, we found better agreement between the ETa simulated and observed by satellite during the dry period, when vegetation activity is maximized. This period is particularly critical for water supply so we can consider it a good approach to conclude with more confidence about the robustness of the proposal.

Finally, our estimations of the avoided costs rely on several assumptions regarding the operational cost, which can be further refined. However, it provides a first estimate of the fiscal expenditure related to forest conservation based on a bill draft as developed by the Chilean political system.

4.2. LULCC and LULCC scenarios

LULCC scenarios are often based on some ad-hoc participatory exercise or on the researchers criteria, but in this study we used the bill for the Recovery of Native Forest and Forest Development (Bulletin No. 669, presented in 1992), as developed by the Chilean political system. Therefore, we introduced a land management scenario that allowed us to discern the likely effects of an early implementation of such a law. This bill assigned monetary incentives for the reforestation of native forest and its management, in addition to prohibiting deforestation. These new incentives and prohibitions are incorporated into the demand estimations and conversion matrix of the Dyna CLUE model. Our simulation of land-cover changes under this scenario indicates that by 2015 there would have been an increase in 5% of native forest area compared to 1990. Therefore, a regulatory policy focused on prohibiting deforestation and promoting forest restoration would have been effective in terms of native forest conservation. However, our simulation also showed an important increase of 88% tree farms from 1990 to 2015 in areas where subsidies for restoration cannot be made effective.

The weakening of the Native Forest Recovery and Forestry Development law can be explained by an extreme interpretation of the property rights over the native forest. This argument was sustained by the generic discourse of the foregone private gains of forest exploitation, if mandatory conservation of native forest was in place (Manuschevich, 2016). In line with this discourse, the idea of fiscal discipline and the restriction of expenditures in payments for conservation were a relevant policy belief that strongly influenced the final outcome. Initially, for the proper implementation of Law 20,283, public expenditure was estimated at 12.13 million USD, but in its fourth stage of constitutional discussion, the annual budget dropped to 5.5 million (Biblioteca del Congreso Nacional de Chile, 2018). Throughout the congressional discussion, the prohibition of native forest replacement was a gridlock point among legislators and stakeholders (Arnold, 2003). As Deputy Alamos expressed: "*The project is inadequate from a socioeconomic point of view. The restrictions and immobilization of potentially productive resources in pursuit of preservation, whatever their benefits, have a cost to society, represented not only by effective monetary flows but also by opportunity costs of future income foregone and jobs lost.*" (First Constitutional Step: Chamber of Deputies Discussion in Chamber). Similar arguments are repeated throughout the discussion of the bill. This is more than domestic politics, as it represents a global discourse regarding the management of natural resources (Dryzek, 2012).

Based on our results, the aforementioned argument can be contrasted from a social welfare perspective.The Chilean government spends a large amount of money to alleviate the deficit of drinking water in rural communities through the supply by water trucks. In a medium-size basin such as Lumaco, around 41,000 USD are spent monthly in water trucks to supply drinking water to rural inhabitants, while in the last 9 years such costs have reached $1,067,388.47, $636,050.00 and $1,369,338.22 USD in the Los Sauces, Purén and Lumaco districts, respectively. This study estimates that an early application of the law with greater environmental protection criteria (NFRP scenario) would have led to an increase of 1,262,277 m^3 in annual water yield in the sub-basins analyzed compared to the 2015 conditions (baseline scenario). The latter could have partially avoided some of the social, economical and environmental costs derived from the ongoing megadrought. In 2018, the water trucks supplied more than 2805 people in the watershed. The amount of water delivered was about 32 l/inh/day, which is far from the 100 l/inh/day established by the WHO (World Health Organization) to cover all the basic needs for one person (WHO, 2003). Only 32 l/inh/day neglects the right of safe access to water and sanitation for all (SDG N°6). Therefore, our estimations are the very first and conservative assessment of the total social costs of increased water scarcity in our study area. We have not included other possible costs, such as lost jobs, rural migration, rural productivity loss, and loss in human welfare (Andersson et al., 2016). For example, Manuschevich (2020) showed how rural livelihoods are completely disrupted if the water is not enough for self-sustenance or feeding household animals, making rural life unfeasible.

In addition, lack of protection and recovery policies for the native forest, as well as the subsidies to tree farms, are key for understanding the substitution of the native forest in Chile. In the Maule, Biobío, and Araucanía regions 14, 13, and 11% of the native forests in place in 1986 have been converted into tree farms in 2011 (Heilmayr et al., 2016), respectively. Moreover, 5% of the previous native loss was a result of the application of DL 701. In the Araucanía region, there has been an increase of 47% in exotic tree farms area since 1970 (Heilmayr et al., 2020), while in the Lumaco catchment, we found that around 8% of the deciduous forest and 16% of the evergreen forest were replaced by tree farms between 1990 and 2015.

4.3. Hydrological response of LULCC scenarios

Yearly simulated ETa values for *Eucalyptus* sp. farms were 731 mm for the entire period (2001–2018), while for the native forest it was 534 mm. Slightly lower amounts were found in Eucalyptus of southern Australia, with transpiration values ranging from 500 to 612 mm, obtained with two different formulations of a process-based ecosystem model (Teskey and Sheriff, 1996). Other studies in Chile estimated ETa yearly values of 545 to 654 mm for *Pinus radiata* plantation (Huber et al., 2008), while Huber et al. (2010) found a 71% of ET/Pp ratio for Eucalipus farms, which is close to the 66% found in our study. This result is also similar to the ET/Pp ratio of 65% obtained by Galleguillos et al. (2021) in a pine farms-dominated catchment. Native forest showed a mean ETa of 534 mm and 729 mm for deciduous forest and evergreen forest, respectively, and an ET/Pp ratio of 50% and 63%. Those result can not be contrasted, since no studies of ETa have been reported for Chilean native forest ecosystems. Thus, a scenario with a greater presence of native forest with respect to tree farms, such as scenarios NFRP and PR, increases the capacity to provide water due to the lower consumption of water by plants with slow growth rates such as native forest species (Almeida et al., 2016; Alvarez-Garreton et al., 2019; van Dijk and Keenan, 2007). In line with other studies, our result shows an increases in summer flows as a result of the increase of native forest area (Lara et al., 2009; Little et al., 2009; Stehr et al., 2010; Iroumé and Palacios, 2013; Little et al., 2015; Galleguillos et al., 2021). However, the absolute increase percentage is lower compared to previous studies developed in Chile. Alvarez-Garreton et al. (2019) found that replacing 10,000 ha of tree farms with Native Forest increases by 5.6% the water supply in a similar catchment in south central Chile. Little et al. (2015) found a 1.4% increase of the run-off coefficient for each meter of increase of streamside buffers of native forest, while Lara et al. (2009) reported an increase of 14% in the summer runoff coefficient for a 10% increase of native forest. In the Cauquenes catchment, located in central Chile, Galleguillos et al. (2021) observed an increase of 11% on flows for scenarios where all tree farms were replaced by native forest. In an other geographical context, but with similar climate conditions, Carvalho-Santos et al. (2016) found an increase of 6% in flows when introducing native forest instead of Eucalyptus farms. No major differences were found when analysing two time periods included in the hydrological simulation, the normal period (2002–2010) and the mega-drought period (2010–2018). We found slight differences on summer flows when comparing precipitation contrasting periods. During a dry year and the mega-dorught period, decreases in Q are simulated, reflecting the decreased in water availability due to the sharp reduction in precipitations during these periods (17%). This reduction in flow due to drought is less important than in other studies such as (Galleguillos et al., 2021; Bozkurt et al., 2018), since this catchment is located in a less water-limited region.

By using alternative scenarios in two small sub-catchments, we also analyzed the impacts of land-cover changes on water provision for the Rural Drinking Water Systems (RDWS). We obtained similar stream flow increments as in the total catchment scale, which is contrary to what is expected according to other studies in small catchments, where a significant increases in flow was reported when increasing native forest area (Little et al., 2015; Lara et al., 2021). Little et al. (2015) found an increased of 1.4% for every square meter in the runoff coefficient where more native forest is introduced, while Lara et al. (2021), reported an increase in flow of 40% to 100% in micro-catchments of less than 5 ha converted from eucalyptus plantation to native forest.

5. Conclusion

We proposed and developed a modeling approach that couples a land-use change (Dyna ClUE) and a hydrological (SWAT) model to evaluate the likely impacts of a native forest recovery policy on some key components of the water balance. The novelty of this methodological approach was to assess and quantify the spatial and hydrological impacts of a scenario based on a bill as discussed by the congress. This integrated methodology, Dyna CLUE and SWAT, shows how potential flow is affected by policies, such as the Native Forest Law. Comparison of simulated values of flows and ETa against ground and satellite observations, respectively, ensured that our coupled-modeling approach was able to adequately represent land-use changes and hydrological components. Therefore, this methodology can assist in the elaboration of land-use planning guidelines, taking into account eco-hydrogical realities and a more realistic assessment of the environmental impact of a given policy. Specially, we assessed the likely effects of a timely implementation of a public policy to protect native forests on catchments used to provided drinking water to vulnerable rural areas dominated by tree farms.

Our results indicate that, in the 2 sub-basins analyzed, the implementation of the NFRP scenario can generate more water than the 3600 m^3 distributed monthly by water trucks to rural population and, therefore, all their associated costs could have been avoided.

Massive afforestation programs, such as The Bonn Challenge and the Trillion Trees Initiative, intend to plant 100.2 Mha with tree farms. Such initiatives must take into consideration the multiple impacts of tree planting over SDGs, while considering the increased global water stress due to climate change, as well as the national and local policies related to the regulation of such endeavors. Current environmental problems are global, they occur on a large scale and include all the subsystems and their interactions. The integrity of forest and the sustainability of its components are global issues. Forests are the results of historical processes that have shaped the evolution of several territories and now define our future. Planning and environmental management on a scientific basis have become a prerequisite for achieving a socio-economic and bio-geophysical sustainable future. The present methodology should, therefore, be seen as a tool to supplement other methodologies for improved environmental management.

CRediT authorship contribution statement

F. Gimeno: Conceptualization, Methodology, Formal analysis, Investigation, Software, Validation, Visualization, Writing – original draft. **M. Galleguillos:** Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing, Visualization. **D. Manuschevich:** Conceptualization, Methodology, Investigation, Supervision, Writing – review & editing. **M. Zambrano-Bigiarini:** Writing – review & editing, Project administration, Conceptualization, Methodology, Software, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.154608.

References

Almeida, A.C., Smethurst, P.J., Siggins, A., Cavalcante, R.B., Borges, N., 2016. Quantifying the effects of Eucalyptus plantations and management on water resources at plot and catchment scales. Hydrol. Process. 30, 4687–4703. https://doi.org/10.1002/hyp.10992.

Alvarez-Garreton, C., Mendoza, P.A., Pablo Boisier, J., Addor, N., Galleguillos, M., Zambrano-Bigiarini, M., Lara, A., Puelma, C., Cortes, G., Garreaud, R., McPhee, J., Ayala, A., 2018. The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies-Chile dataset. Hydrol. Earth Syst. Sci. 22, 5817–5846. https://doi.org/10.5194/hess-22-5817-2018.

Alvarez-Garreton, C., Lara, A., Boisier, J.P., Galleguillos, M., 2019. The impacts of native forests and forest plantation on water supply in Chile. Forests 10, 473. https://doi.org/10.3390/f10060473.

AMEOANNA, 2020. 222 mil millones gastó el Estado en contratar camiones aljibe y más de $11 mil millones en comprar forraje para ganado.

Andersson, K., Lawrence, D., Zavaleta, J., Guariguata, M.R., 2016. More Trees, More Poverty? The Socioeconomic Effects of Tree Plantations in Chile, 2001–2011. 57, pp. 123–136. https://doi.org/10.1007/s00267-015-0594-x.

Armesto, J.J., Manuschevich, D., Mora, A., Smith-Ramirez, C., Rozzi, R., Abarzúa, A.M., Marquet, P.A., 2010. From the Holocene to the Anthropocene: a historical framework for land cover change in southwestern South America in the past 15,000 years. Land Use Policy 27, 148–160. https://doi.org/10.1016/j.landusepol.2009.07.006.

Arnold, F.E., 2003. Native forest policy in Chile: understanding sectoral process dynamics in a country with an emerging economy. Int. For. Rev. 5, 317–328. https://doi.org/10.1505/IFOR.5.4.317.22662.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. LARGE AREA HYDROLOGIC MODELING AND ASSESSMENT PART I : MODEL DEVELOPMENT basin scale model called SWAT (Soil and Water speed and storage, advanced software debugging policy to meet the needs, and the management to the tank model (Sugawara et al., 1 34, 73–89.

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., van Griensven, A., Van Liew, M.W., Kannan, N., Jha, M.K., 2012. SWAT: model use, calibration, and validation. Trans. ASABE 55, 1491–1508.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A., Wood, E.F., 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. Sci. Data 5, 1–12. https://doi.org/10.1038/sdata.2018.214.

Biblioteca del Congreso Nacional de Chile, 2018. Historia de la Ley 20.283. Ley sobre recuperación del bosque nativo y fomento forestal. Technical Report. BCN, Valparaíso.

Birkinshaw, S.J., Bathurst, J.C., Iroumé, A., Palacios, H., 2011. The effect of forest cover on peak flow and sediment discharge-an integrated field and modelling study in central-southern Chile. Hydrol. Process. 25, 1284–1297. https://doi.org/10.1002/hyp.7900.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55, 3–23. https://doi.org/10.1016/0022-1694(82)90117-2.

Bozkurt, D., Rojas, M., Boisier, J.P., Valdivieso, J., 2018. Projected hydroclimate changes over Andean basins in central Chile from downscaled CMIP5 models under the low and high emission scenarios. Clim. Chang. 150, 131–147. https://doi.org/10.1007/s10584-018-2246-7.

Brown, D.G., Verburg, P.H., Pontius, R.G., Lange, M.D., 2013. Opportunities to improve impact, integration, and evaluation of land change models. Curr. Opin. Environ. Sustain. 5, 452–457. https://doi.org/10.1016/j.cosust.2013.07.012.

Bullock, A., Acreman, M., 2003. The role of wetlands in the hydrological cycle. Hydrol. Earth Syst. Sci. 7, 358–389. https://doi.org/10.5194/hess-7-358-2003.

Camus, P., 2006. Ambiente, bosques y gestión forestal en Chile. volume 40. Dibam, pp. 1541–2005.

Carvalho-Santos, C., Nunes, J.P., Monteiro, A.T., Hein, L., Honrado, J.P., 2016. Assessing the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal. Hydrol. Process. 30, 720–738. https://doi.org/10.1002/hyp.10621.

Chen, M., Senay, G.B., Singh, R.K., Verdin, J.P., 2016. Uncertainty analysis of the operational simplified surface energy balance (SSEBop) model at multiple flux tower sites. J. Hydrol. 536, 384–399. https://doi.org/10.1016/j.jhydrol.2016.02.026.

CIREN, 2002. Estudio agrológico Región de La Araucanía: descripción de suelos materiales y símbolos. Technical Report. Centro de Información de Recursos Naturales (Chile), Santiago.

Cohen, J., 1960. A coefficient of agreement for nominal scales. Educ. Psychol. Meas. 20, 37–46. https://doi.org/10.1177/001316446002000104.

Crockford, R.H., Richardson, D.P., 1990. Partitioning of rainfall in a eucalypt forest and pine plantation in southeastern Australia: II stemflow and factors affecting stemflow in a dry sclerophyll eucalypt forest and a Pinus radiata plantation. Hydrol. Process. 4, 145–155. https://doi.org/10.1002/hyp.3360040205.

Cubbage, F., Mac Donagh, P., Sawinski, J., Rubilar, R., Donoso, P., Ferreira, A., Hoeflich, V., Olmos, V.M., Ferreira, G., Balmelli, G., Siry, J., Báez, M.N., Alvarez, J., 2007. Timber investment returns for selected plantations and native forests in South America and the southern United States. New For. 33, 237–255. https://doi.org/10.1007/s11056-006-9025-4.

DGA, 2014. Base Agua Potable Rural. Technical Report. Dirección General de Aguas, Ministerio de Obras Públicas, Santiago.

DGA, 2016. Atlas del Agua. Atlas del Agua Chile 2016. 1, pp. 1–24.

Dias, L.C.P., Macedo, M.N., Costa, M.H., Coe, M.T., Neill, C., 2015. Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil. J. Hydrol. Reg. Stud. 4, 108–122. https://doi.org/10.1016/j.ejrh.2015.05.010.

van Dijk, A.I., Keenan, R.J., 2007. Planted forests and water in perspective. For. Ecol. Manag. 251, 1–9. https://doi.org/10.1016/j.foreco.2007.06.010.

Dile, Y., Srinivasan, R., George, C., 2015. QGIS Interface for SWAT+: (QSWAT+). Setup for Robit Watershed, Lake Tana Basin, pp. 1–118 https://doi.org/10.13140/RG.2.1.1060.7201.

Dingman, S.L., 2015. PHYSICAL. Third edition. .

Dodd, L.E., Pepe, M.S., 2003. Semiparametric regression for the area under the receiver operating characteristic curve. J. Am. Stat. Assoc. 98, 409–417. https://doi.org/10.1198/016214503000198.

Dryzek, J.S., 2012. The Politics of the Earth: Environmental Discourses. 3 ed. Oxford University Press https://doi.org/10.1093/hepl/9780199696000.001.0001.

Eckhardt, K., Arnold, J.G., 2001. Automatic calibration of a distributed catchment model. J. Hydrol. 251, 103–109. https://doi.org/10.1016/S0022-1694(01)00429-2.

Forrester, D., Collopy, J., Morris, J., 2010a. Transpiration along an age series of Eucalyptus globulus plantations in southeastern Australia. For. Ecol. Manag. 259, 1754–1760. https://doi.org/10.1016/j.foreco.2009.04.023.

Forrester, D., Theiveyanathan, S., Collopy, J.J., Marcar, N.E., 2010b. Enhanced water use efficiency in a mixed Eucalyptus globulus and Acacia mearnsii plantation. For. Ecol. Manag. 259, 1761–1770. https://doi.org/10.1016/j.foreco.2009.07.036.

Friesen, J., Zink, M., Bawain, A., Müller, T., 2018. Hydrometeorology of the Dhofar cloud forest and its implications for groundwater recharge. J. Hydrol. Reg. Stud. 16, 54–66. https://doi.org/10.1016/j.ejrh.2018.03.002.

Galleguillos, M., Gimeno, F., Puelma, C., Zambrano-Bigiarini, M., Lara, A., Rojas, M., 2021. Disentangling the effect of future land use strategies and climate change on streamflow in a Mediterranean catchment dominated by tree plantations. J. Hydrol. 595, 126047. https://doi.org/10.1016/j.jhydrol.2021.126047.

Garreaud, R., Falvey, M., Montecinos, A., 2016. Orographic precipitation in coastal Southern Chile: mean distribution, temporal variability, and linear contribution. J. Hydrometeorol. 17, 1185–1202. https://doi.org/10.1175/jhm-d-15-0170.1.

Garreaud, R., Alvarez-Garreton, C., Barichivich, J., Boisier, J.P., Christie, D., Galleguillos, M., LeQuesne, C., McPhee, J., Zambrano-Bigiarini, M., 2017. The 2010–2015 mega drought in Central Chile: impacts on regional hydroclimate and vegetation. Hydrol. Earth Syst. Sci. Discuss., 1–37 https://doi.org/10.5194/hess-2017-191.

Garreaud, R., Boisier, J.P., Rondanelli, R., Montecinos, A., Sepúlveda, H., Veloso-Aguila, D., 2020. The Central Chile Mega Drought (2010–2018): a climate dynamics perspective. Int. J. Climatol. 40, 421–439. https://doi.org/10.1002/joc.6219.

González, M.J., Vargas, M.H., Vásquez, P.N., 2020. Hydrological response to land use scenarios under climate change. Adaptation measures for an agricultural basin: Rapel river basin in central Chile. EGU General Assembly 2020, Online. 2020. https://doi.org/10.5194/egusphere-egu2020-11462.

van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., Srinivasan, R., 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. J. Hydrol. 324, 10–23. https://doi.org/10.1016/j.jhydrol.2005.09.008.

Griscom, B.W., Ellis, P., Houghton, R.A., Lomax, G., Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., 2017. Natural climate solutions. PNAS https://doi.org/10.1073/pnas.1710465114.

Heilmayr, R., Echeverría, C., Fuentes, R., Lambin, E.F., 2016. A plantation-dominated forest transition in Chile. Appl. Geogr. 75, 71–82. https://doi.org/10.1016/j.apgeog.2016.07.014.

Heilmayr, R., Echeverría, C., Lambin, E.F., 2020. Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity. Nat. Sustain. 3, 701–709. https://doi.org/10.1038/s41893-020-0547-0.

Huber, A., Iroume, A., Bathurst, J., 2008. Effect of Pinus radiata plantations on water balance in Chile. Hydrol. Process. 22, 142–148. https://doi.org/10.1002/hyp.6582.

Huber, A., Iroumé, A., Mohr, C., Frêne, C., 2010. Efecto de plantaciones de Pinus radiata y Eucalyptus globulus sobre el recurso agua en la Cordillera de la Costa de la región del Biobío, Chile. Bosque 31, 219–230. https://doi.org/10.4067/S0717-92002010000300006.

Ilustre Municipalidad de Lumaco, 2014. Plan de Desarrollo Comunal Lumaco 2015-2018. Technical Report. Ilustre Municipalidad de Lumaco, Lumaco.

Ilustre Municipalidad de Purén, 2017. Plan de Desarrollo Comunal 2017-2021. Technical Report. Ilustre Municipalidad de Purén, Purén.

INE, 2017. Censo de población y vivienda 2017. Technical Report. Instituto Nacional de Estadistica, Santiago.

INFOR, 2019. Anuario Forestal (Chilean Statistical Yearbook of Forestry) 2019. Infor. ISBN: 978-956-318-098-5, pp. 1–154.

Iroumé, A., Palacios, H., 2013. Afforestation and changes in forest composition affect runoff in large river basins with pluvial regime and Mediterranean climate, Chile. J. Hydrol. 505, 113–125. https://doi.org/10.1016/j.jhydrol.2013.09.031.

Khanal, S., Parajuli, P.B., 2014. Sensitivity analysis and evaluation of forest biomass production potential using SWAT model. J. Sustain. Bioenergy Syst. 04, 136–147. https://doi.org/10.4236/jsbs.2014.42013.

Kim, I., Arnhold, S., Ahn, S., Le, Q.B., Kim, S.J., Park, S.J., Koellner, T., 2019. Land use change and ecosystem services in mountainous watersheds: predicting the consequences of environmental policies with cellular automata and hydrological modeling. Environ. Model. Softw. 122, 103982. https://doi.org/10.1016/j.envsoft.2017.06.018.

Komatsu, H., Kume, T., Otsuki, K., 2011. Increasing annual runoff-broadleaf or coniferous forests? Hydrol. Process. 25, 302–318. https://doi.org/10.1002/hyp.7898.

Lara, A., Little, C., Urrutia, R., McPhee, J., Álvarez-Garretón, C., Oyarzún, C., Soto, D., Donoso, P., Nahuelhual, L., Pino, M., Arismendi, I., 2009. Assessment of ecosystem services as an opportunity for the conservation and management of native forests in Chile. For. Ecol. Manag. 258, 415–424. https://doi.org/10.1016/j.foreco.2009.01.004.

Lara, A., Jones, J., Little, C., Vergara, N., 2021. Streamflow response to native forest restoration in former Eucalyptus plantations in south central Chile. Hydrol. Process. 35, 1–17. https://doi.org/10.1002/hyp.14270.

Lewis, S.L., Maslin, M.A., 2015. Defining the Anthropocene. Nature 519, 171–180. https://doi.org/10.1038/nature14258.

Lewis, S.L., Wheeler, C.E., Mitchard, E.T.A., Koch, A., 2019. Regenerate natural forest to store carbon. Nature 568, 25–28.

Li, G., Zhang, F., Jing, Y., Liu, Y., Sun, G., 2017. Response of evapotranspiration to changes in land use and land cover and climate in China during 2001–2013. Sci. Total Environ. 596–597, 256–265. https://doi.org/10.1016/j.scitotenv.2017.04.080.

van Liew, M.W., Arnold, J.G., Bosch, D.D., 2005. Problems and potential of autocalibrating a hydrologic model. Trans. Am. Soc. Agric. Eng. 48, 1025–1040. https://doi.org/10.13031/2013.18514.

Lima, M.L., Zelaya, K., Massone, H., 2011. Groundwater vulnerability assessment combining the drastic and Dyna-CLUE model in the Argentine Pampas. Environ. Manag. 47, 828–839. https://doi.org/10.1007/s00267-011-9652-1.

Little, C., Lara, A., McPhee, J., Urrutia, R., 2009. Revealing the impact of forest exotic plantations on water yield in large scale watersheds in South-Central Chile. J. Hydrol. 374, 162–170. https://doi.org/10.1016/j.jhydrol.2009.06.011.

Little, C., Cuevas, J.G., Lara, A., Pino, M., Schoenholtz, S., 2015. Buffer effects of streamside native forests on water provision in watersheds dominated by exotic forest plantations. Ecohydrology 8, 1205–1217. https://doi.org/10.1002/eco.1575.

Luebert, F., Pliscoff, P., 2018. Sinopsis bioclimática y vegetacional de Chile. Editorial Universitaria, Santiago.

Manuschevich, D., 2016. Neoliberalization of forestry discourses in Chile. For. Policy Econ. 69, 21–30. https://doi.org/10.1016/j.forpol.2016.03.006.

Manuschevich, D., 2018. A critical assessment of the adaptative capacity of land use change in Chile: a socio-ecological approach. In: Loures, L. (Ed.), Land Use - Assessing the Past, Envisioning the Future. INTECHOPEN, p. 13 https://doi.org/10.5772/intechopen.80559.

Manuschevich, D., 2020. Land use as a socio-ecological system: developing a transdisciplinary approach to studies of land use change in South-Central Chile. Ecological Economic and Socio Ecological Strategies for Forest Conservation: A Transdisciplinary Approach Focused on Chile and Brazil, pp. 79–97 https://doi.org/10.1007/978-3-030-35379-7 5.

Manuschevich, D., Beier, C.M., 2016. Simulating land use changes under alternative policy scenarios for conservation of native forests in south-central Chile. Land Use Policy 51, 350–362. https://doi.org/10.1016/j.landusepol.2015.08.032.

Manuschevich, D., Sarricolea, P., Galleguillos, M., 2019. Integrating socio-ecological dynamics into land use policy outcomes: a spatial scenario approach for native forest conservation in south-central Chile. Land Use Policy 84, 31–42. https://doi.org/10.1016/j.landusepol.2019.01.042.

Memarian, H., Balasundram, S.K., Abbaspour, K.C., Talib, J.B., Boon Sung, C.T., Sood, A.M., 2014. Modélisation hydrologique de scénarios d'utilisation des sols en zone tropicale à l'aide du modèle SWAT. Hydrol. Sci. J. 59, 1808–1829. https://doi.org/10.1080/02626667.2014.892598.

Mercado Publico, 2017. CONTRATO DE SUMINISTRO CAMIONES ALJIBES PERIODO 2017-2018. Technical Report.

Moletto-Lobos, I., Mattar, C., Barichivich, J., 2020. Performance of satellite-based evapotranspiration models in temperate pastures of southern Chile. Water (Switzerland) 12, 1–16. https://doi.org/10.3390/w12123587.

Moriasi, D.N., Arnold, J., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153.

Moriasi, D.N., Zeckoski, R.W., Arnold, J.G., Baffaut, C.B., Malone, R.W., Daggupati, P., Guzman, J.A., Saraswat, D., Yuan, Y., Wilson, B.W., Shirmohammadi, A., Douglas-Mankin, K.R., 2015. Hydrologic and water quality models: key calibration and validation topics. Trans. ASABE 58, 1609–1618. https://doi.org/10.13031/trans.58.11075.

Nash, J.E., Sutcliffe, J., 1970. River flow forecasting through conceptual models part I — a discussion of principles. J. Hydrol. 10, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6.

Neitsch, S., Arnold, J., Kiniry, J., 2005. Herramienta de evaluación de suelo y agua documentación teórica. 415. Agricultural Research Service.

Neitsch, S., Arnold, J., Kiniry, J., Williams, J., 2011. Soil & Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute, pp. 1–647 https://doi.org/10.1016/j.scitotenv.2015.11.063.

Niklitschek, M.E., 2007. Trade liberalization and land use changes: explaining the expansion of afforested land in Chile. For. Sci. 53, 385–394. https://doi.org/10.1093/forestscience/53.3.385.

OCDE, 2016. Estudios de Política Rural de la OCDE- Chile. 206.

ONEMI, 2017. Oficio N° 48/217. Technical Report. Oficina Nacional de Emegrencia, Temuco.

Oyarzun, C., Aracena, C., Rutherford, P., Godoy, R., Deschrijver, A., 2007. Effects of land use conversion from native forests to exotic plantations on nitrogen and phosphorus retention in catchments of southern Chile. Water Air Soil Pollut. 179, 341–350. https://doi.org/10.1007/s11270-006-9237-4.

Pindozzi, S., Cervelli, E., Recchi, P.F., Capolupo, A., Boccia, L., 2017. Predicting land use change on a broad area: Dyna-CLUE model application to the Litorale Domizio-Agro Aversano (Campania, South Italy). J. Agric. Eng. 48. https://doi.org/10.4081/jae.2017.657.

Poblete, A.G., Antonella, A.M., Vera, M.J., 2017. Cuantificación de la incidencia del ENSO en las nevadas de Los Andes áridos de Sudamérica en el perioodo 1909-2015. Revista Geográfica Digital. 27. IGUNNE.

Rahman, M.S., Islam, M., 2020. Water Science. volume I. https://doi.org/10.1002/9781119651123.ch2.

Romano, G., Abdelwahab, O.M., Gentile, F., 2018. Modeling land use changes and their impact on sediment load in a Mediterranean watershed. Catena 163, 342–353. https://doi.org/10.1016/j.catena.2017.12.039.

Sands, R., Nambiar, E.K., 1984. Water relations of Pinus radiata in competition with weeds. Can. J. For. Res. 14, 233–237. https://doi.org/10.1139/x84-045.

Senay, G.B., 2018. Satellite psychrometric formulation of the operational simplified surface energy balance (Ssebop) model for quantifying and mapping evapotranspiration. Appl. Eng. Agric. 34, 555–566.

Serpa, D., Nunes, J.P., Santos, J., Sampaio, E., Jacinto, R., Veiga, S., Lima, J.C., Moreira, M., Corte-Real, J., Keizer, J.J., Abrantes, N., 2015. Impacts of climate and land use changes on the hydrological and erosion processes of two contrasting Mediterranean catchments. Sci. Total Environ. 538, 64–77. https://doi.org/10.1016/j.scitotenv.2015.08.033.

Soil Science Division Staff, 2017. Soil Survey Manual. volume 3. Government Printing Office, Washington, D.C.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347. https://doi.org/10.1126/science.1259855.

Stehr, A., Aguayo, M., Link, O., Parra, O., Romero, F., Alcayaga, H., 2010. Modelling the hydrologic response of a mesoscale Andean watershed to changes in land use patterns for environmental planning. Hydrol. Earth Syst. Sci. 14, 1963–1977. https://doi.org/10.5194/hess-14-1963-2010.

Stocker, B.D., Strassmann, K., Joos, F., 2011. Sensitivity of Holocene atmospheric CO2 and the modern carbon budget to early human land use: analyses with a process-based model. Biogeosciences 8, 69–88. https://doi.org/10.5194/bg-8-69-2011.

Teskey, R.O., Sheriff, D.W., 1996. Water use by Pinus radiata trees in a plantation. Tree Physiol. 16, 273–279. https://doi.org/10.1093/treephys/16.1-2.273.

UNCCD, 2017. The Future Strategic Framework of the Convention. Technical Report. United Nation Convention to Combat Desertification, Ordos.

United Nation, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. Technical Report A/70/L.1. https://doi.org/10.1163/157180910X12665776638740.

Velpuri, N.M., Senay, G.B., Singh, R.K., Bohms, S., Verdin, J.P., 2013. A comprehensive evaluation of two MODIS evapotranspiration products over the conterminous United States: using point and gridded FLUXNET and water balance ET. Remote Sens. Environ. 139, 35–49. https://doi.org/10.1016/j.rse.2013.07.013.

Venkatesh, K., Preethi, K., Ramesh, H., 2020. Evaluating the effects of forest fire on water balance using fire susceptibility maps. Ecol. Indic. 110. https://doi.org/10.1016/j.ecolind.2019.105856.

Verburg, P.H., Overmars, K.P., 2009. Combining top-down and bottom-up dynamics in land use modeling: exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model. Landsc. Ecol. 24, 1167–1181. https://doi.org/10.1007/s10980-009-9355-7.

van Vliet, J., Bregt, A.K., Hagen-Zanker, A., 2011. Revisiting Kappa to account for change in the accuracy assessment of land-use change models. Ecol. Model. 222, 1367–1375. https://doi.org/10.1016/j.ecolmodel.2011.01.017.

van Vliet, J., Bregt, A.K., Brown, D.G., van Delden, H., Heckbert, S., Verburg, P.H., 2016. A review of current calibration and validation practices in land-change modeling. Environ. Model. Softw. 82, 174–182. https://doi.org/10.1016/j.envsoft.2016.04.017.

WHO, 2003. Domestic Water Quantity, Service Level and Health. Technical Report. World Health Organization, Geneva.

Wolff, S., Schrammeijer, E.A., Schulp, C.J., Verburg, P.H., 2018. Meeting global land restoration and protection targets: what would the world look like in 2050? Glob. Environ. Chang. 52, 259–272. https://doi.org/10.1016/j.gloenvcha.2018.08.002.

Yang, Q., Zhang, X., 2016. Improving SWAT for simulating water and carbon fluxes of forest ecosystems. Sci. Total Environ. 569–570, 1478–1488. https://doi.org/10.1016/j.scitotenv.2016.06.238 URL: 10.1016/j.scitotenv.2016.06.238.

Yang, Q., Almendinger, J.E., Zhang, X., Huang, M., Chen, X., Leng, G., Zhou, Y., Zhao, K., Asrar, G.R., Srinivasan, R., Li, X., 2018. Enhancing SWAT simulation of forest ecosystems for water resource assessment: a case study in the St. Croix River basin. Ecol. Eng. 120, 422–431. https://doi.org/10.1016/j.ecoleng.2018.06.020 URL: 10.1016/j.ecoleng.2018.06.020.

Yang, Q., Zhang, X., Almendinger, J.E., Huang, M., Leng, G., Zhou, Y., Zhao, K., Asrar, G.R., Li, X., Qiu, J., 2019. Improving the SWAT forest module for enhancing water resource projections: a case study in the St.Croix River basin. Hydrol. Process. 33, 864–875. https://doi.org/10.1002/hyp.13370.

Yin, L., Wang, X., Feng, X., Fu, B., Chen, Y., 2020. A comparison of SSEBop-model-based evapotranspiration with eight evapotranspiration products in the Yellow River Basin, China. Remote Sens. 12. https://doi.org/10.3390/RS12162528.

Zambrano-Bigiarini, M., Clerc, M., Rojas, R., 2013. Standard Particle Swarm Optimisation 2011 at CEC-2013: a baseline for future PSO improvements. 2013 IEEE Congress on Evolutionary Computation, CEC 2013, pp. 2337–2344 https://doi.org/10.1109/CEC.2013.6557848.

Zhang, L., Nan, Z., Xu, Y., Li, S., 2016. Hydrological impacts of land use change and climate variability in the headwater region of the Heihe River Basin, northwest China. PLoS ONE 11, 1–25. https://doi.org/10.1371/journal.pone.0158394.

Zhao, Y., Feng, D., Yu, L., Wang, X., Chen, Y., Bai, Y., Hernández, H.J., Galleguillos, M., Estades, C., Biging, G.S., Radke, J.D., Gong, P., 2016. Detailed dynamic land cover mapping of Chile: accuracy improvement by integrating multi-temporal data. Remote Sens. Environ. 183, 170–185. https://doi.org/10.1016/j.rse.2016.05.016.

Zhuang, Q., Shi, Y., Shao, H., Zhao, G., Chen, D., 2021. Evaluating the ssebop and rspmpt models for irrigated fields daily evapotranspiration mapping with modis and cmads data. Agriculture (Switzerland) 11. https://doi.org/10.3390/agriculture11050424.