Streamflow response to native forest restoration in former *Eucalyptus* plantations in south central Chile

Antonio Lara[1], Julia Jones[2], Christian Little[3], and Nicolás Vergara[1]

[1]Universidad Austral de Chile
[2]Oregon State University
[3]INFOR

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Abstract

This study presents the results of a long-term paired catchment experiment in south central Chile (mean annual precipitation = 2,500 mm, 5% falling in summer, mean annual temperature = 10 °C) in which fast-growing plantations of exotic *Eucalyptus* spp. were clearcut and replaced with native temperate rainforest species as part of an ecological restoration project. Precipitation, streamflow, and vegetation were measured starting in 2006 in four small (3 to 5 ha) catchments with *Eucalyptus globulus* plantations and native riparian buffers in the Valdivian Coastal Reserve. In 2011, the 12-yr-old *Eucalyptus* plantations were harvested in three catchments, and the clearcut area was planted with native trees (*Nothofagus dombeyi*), and diverse native forest species regenerated vigorously. In the restoration period (2011 to 2019), annual streamflow increased in average by 21 – 73% compared to the 2006-2010 pre-treatment period, and as much as 100% in wet years and by more than 150% in fall and summer of some years. Streamflow was 50 to 100% lower than before treatment in two dry summers (2014-2015. Base flow increased by 28 to 87% during the restoration period (2011 to 2019) compared to the pre-treatment period, and remained elevated in later years despite low summer precipitation. Streamflow increases persisted through the first decade of restoration. Overall, these findings indicate that removal of *Eucalyptus* plantations immediately increased streamflow, and native forest restoration gradually restored deep soil moisture reservoirs that sustain base flow during dry periods, and these flows showed steady positive values in the last three years contributing to water provision ecosystem services. The results of this study are relevant to efforts to restore native forest ecosystems on land currently intensively managed fast-growing forest plantations. They also provide useful information to inform policy and decision-making related to options for climate change mitigation under a drying trend in South-central Chile. To our knowledge this study is the first to test streamflow response to native forest restoration in former fast-growing *Eucalyptus* forest plantations.

1. Introduction

Global forests are changing rapidly to produce fiber, food and other products (Hansen et al., 2013). Despite their central relevance to global sustainability goals and ecosystem services, including water provision and streamflow regulation, natural forests are being lost in many regions of the world including South America (Creed & van Noordwijk, 2018; Creed et al., 2019; Jones et al., 2017; Paquette & Messier, 2010). Temperate rainforests of south central Chile are a global biodiversity hotspot containing highly threatened endemic species (Olson & Dinerstein, 1998). Since 1974, much of the area of native forests in central Chile has been converted to fast growing plantations of exotic *Pinus radiata* and *Eucalyptus* species, or to shrublands, agriculture and pastureland (Aguayo, Pauchard, Azócar, & Parra, 2009; Echeverría et al., 2006; Miranda, Altamirano, Cayuela, Lara, & González, 2016). These changes have been associated with declining annual and summer runoff in small and large catchments (Lara et al., 2009; Little, Lara, McPhee, & Urrutia, 2009; Iroumé & Palacios, 2013) as well as reduced plant diversity (Altamirano, Echeverría, & Lara, 2007) and carbon storage (Hall, van Holt, Daniels, Balthazar, & Lambin, 2012; Heilmayr, Echeverría, & Lambin, 2020).

Ecological restoration aims to increase biodiversity and increase the provision of diverse ecosystem services (Benayas, Newton, Diaz, & Bullock, 2009). Ecological restoration is defined as the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (Gann et al., 2019). Restoration efforts attempt to increase native forest cover, species diversity, ecosystem functionality, and ecosystem services such as water provision and regulation (Little & Lara 2010; Clewell & Aronson, 2013). Functional ecological restoration includes efforts specifically targeted at restoring critical structural ecosystem features such as native vegetation, and ecological processes such as nutrient dynamics (Palmer, Hondula, & Koch, 2014).

Ecological restoration is distinct from afforestation, but these two contrasting concepts are sometimes confused in the hydrological literature. Afforestation with fast-growing species has been linked to adverse hydrologic effects such as reduced streamflow (Farley, Jobbágy, & Jackson, 2005; Filoso, Bezerra, Weiss, & Palmer, 2017) and groundwater (Lu, Zhao, Shi, & Cao, 2018). In contrast, the restoration of native vegetation is intended to restore forest hydrology. For example, native forest restoration was associated with increased soil moisture and water table levels and increased forest biodiversity, including plants, fungi, and lichens (Mazziotta et al., 2016).

This study addresses a gap in knowledge about hydrologic response to forest restoration. We describe a 14-year (2006 to 2019) catchment study to determine how streamflow responded to the first nine years of a 130 to 180-year forest restoration experiment (Lara, Little, González, & Lobos, 2013). After five years of pre-treatment streamflow measurements,*Eucalyptus globulus* plantations were clear-cut in 2011. Restoration was initiated by this clearcut, followed by planting seedlings of native *Nothofagus dombeyi* tree species and fostering regeneration of other native species. The study is located in the Valdivian Coastal Reserve in south central Chile, a Nature Conservancy (TNC) reserve on former private industrial forest land. This study is one of the longest catchment experiments in South America, and to our knowledge, the only one involving a long-term effort to restore native forests on land formerly in short-rotation intensively managed forest plantations.

This study addressed the following questions:

1. How did streamflow respond to restoration of native forest in former*Eucalyptus* plantations?
2. How has native vegetation changed in catchments under restoration?
3. What factors explain variation in streamflow response?

2. Study site and Methods

2.1. Study site, experimental treatments

The study was conducted in the Valdivian Coastal Reserve on the coast of south central Chile (39°58'S, 73°33'W) (Figure 1). Mean annual precipitation is 2500 mm and mean annual temperature is 10°C; 95% of precipitation occurs in fall, winter, and spring. The geology consists of Paleozoic metamorphic rocks, partially overlaid by Tertiary marine sediments with a slope of 30° (60%). Soils have a volcanic origin and are Typic Haplohumults (Ultisols, Hueycolla series) with a low pH (4.2–4.8) (CIREN, 2001).

Prior to the conversion to *Eucalypt* plantations in the 1990s, the vegetation of the study site was Valdivian temperate evergreen forest in areas of abundant annual precipitation (2000 to 5000 mm) from near sea level to nearly 1000 m in the Andes and the Coastal Cordillera from 38°30' to 47°S (Veblen, Donoso, Kitzberger, & Rebertus, 1996). These forests are dominated by approximately fifteen species, most of which are endemic to south central Chile and adjacent areas of Argentina (Donoso, 2006). Historically, native forests of the study site were selectively logged by local people for wood and wood fuels. Between 1993 and 1999, 3000 ha of native forests in this area were clear-cut, burned, and converted to exotic *Eucalyptus* plantations (Little, Lara, & González, 2013; Lara et al., 2014). In 2003, The Nature Conservancy purchased an area of 500 km^2 from the timber company that established the *Eucalyptus* plantations and created a reserve to protect rainforests and coastal marine ecosystems. At the start of the experiment in 2006, vegetation in the study catchments consisted of 7-yr-old commercial plantations of *Eucalyptus globulus* and native forest along streamside buffers (Table 1).

The paired-catchment study is a collaborative agreement among Universidad Austral de Chile (UACh), The Nature Conservancy (TNC) and Masisa S.A., a private forestry company. Masisa S.A. harvested*Eucalyptus* plantations and planted native tree species in a 45-ha pilot area within the Valdivian Coastal Reserve. In conjunction with TNC and Masisa S.A., UACh managed the design and planning of the restoration experiment including monitoring of streamflow, precipitation and permanent vegetation plots. TNC owns, protects and manages the site.

Precipitation and stream gaging began in 2006 in four small catchments (Figure 1, Figure 2). Catchment size ranges from 3.7 to 5.3 ha, elevation ranges from 6 to 195 m, and mean slope gradient is 41 to 47% (Table 1). In 2010, *Eucalyptus* plantations occupied 64 to 76% of catchment area, and native forest riparian buffers occupied 24 to 36% of catchment area. *Eucalyptus* plantations in catchments RC5, RC10 and RC11 were clear-cut in February to April of 2011, when the plantations were 12 years of age (Table 1). Clear-cut catchments were replanted in 2011 with a native tree species, *Nothofagus dombeyi*at a density of 1,500 seedlings/ha, with supplemental planting in 2012 (Little et al., 2013, Lara et al., 2014). *Nothofagus dombeyi* is a dominant species in the forests of south central Chile; it may reach 40 m in height (Donoso, 2006). It was chosen because it is a pioneer fast-growing species that is present in the Reserve, and therefore it was expected to rapidly form closed-canopy forest stands (Lara et al., 2013). Areas under restoration were fenced to exclude cattle, and cut stumps of *Eucalyptus* were treated with herbicide in catchments RC10 and RC11 but not in catchment RC5. Native trees (fifteen species) have seeded in from nearby forest stands, and together with regenerating shrubs, ferns and epiphytes have produced a diverse young forest in the areas that were planted with *Nothofagus* spp. (Lara et al., 2013, Lara et al., 2014). This study covers five years prior to the clear-cutting of *Eucalyptus* (2006 to 2010, the pre-treatment period) and nine years after clear-cutting the *Eucalyptus* and planting of native trees in RC5, RC10, and RC11, as well as continued growth of the *Eucalyptus* plantation in RC6 (2011 to 2019, the post-treatment period or the period under restoration).

2.2. Field data collection

Precipitation has been measured in canopy openings at five sites over varied periods since February 2006 (Little, Cuevas, Lara, Pino, & Schoenholtz, 2014) (Figure 1) using tipping-bucket gages (Model DAVIS 7852) with a resolution of 0.2 mm, equipped with HOBO event loggers. Precipitation data were compiled on a daily basis. A complete record of daily precipitation for the period April 2006 through March 2020 was created for the rain gage nearest to the four study catchments based on linear relationships with other stations (R^2 ranged from 0.94 to 0.98).

Streamflow is measured using 90° V-notch weirs constructed in 2006 (RC5, RC6) and 2008 (RC10, RC11) (Little et al., 2014). The water year starts in April (fall) of the named year and ends in March (summer) of the following year. Stage height was measured manually for water years 2006 to 2008 in RC5 and RC6 and using automated measurements at all catchments for water years 2009 to present. Atmospheric pressure and water pressure at the weir were measured at all stream gaging locations using pressure transducers (HOBO U20-001, with a resolution of 40 Pa). Data were downloaded, compiled at 15-minute resolution, quality checked, converted to discharge and summarized at the daily scale. Mean daily streamflow for each day of the record was expressed on a unit-area basis (mm). Missing values of daily streamflow were filled based on adjacent values (for gaps of one to three days) and relationships with precipitation (see below) for longer gaps. Analyses reported here used observed streamflow for RC5 and RC6 (2006 through 2019) and RC10 and RC11 (2009 through 2019) and filled values for RC10 and RC11 (2006 through 2008). The resulting dataset will be available after publication from*http://www.cr2.cl/datos-cuencas-restauracion-reservavaldiviana/* .

Eucalyptus plantations were surveyed in 2010, prior to clear-cutting, by Masisa S.A. (Figure 2). Permanent vegetation plots were established in the understory of the *Eucalyptus* plantations before they were clear-cut in 2011 (Figure 2). Each circular plot is 12.6 m radius and 500 m^2 and contains 20, 1-m radius subplots distributed at 3 m intervals along the cardinal axes. Data on survival, health, height, and diameter at breast height (dbh) were obtained for *N. dombeyi* and *Eucalyptus* individuals in two quadrants of the 500 m^2 plot. The number of seedlings (< 2 m height), saplings (> 2 m, <5 cm dbh), and trees (dbh > 5cm) and the cover of all non-tree species was recorded in the subplots. Plots were measured in 2010, 2012, 2014, and 2016. Of the 45 plots established in 2010 in the total restored area, four were in RC11, two were in RC5, and one was in RC10. In 2020, plots were resampled and additional vegetation plots of the same design were installed to provide equal sampling density (four plots in each study catchment) (Figure 2). In 2020, one vegetation plot was also established in the native vegetation buffer in RC5, RC10 and RC11, and three plots were sampled in RC6 to determine basal area of*Eucalyptus* .

2.3. Data analyses

Three methods were applied to estimate the effects of the treatment on streamflow: (1) double-mass plots and runoff ratios; (2) a before-after analysis contrasting post-treatment streamflow to pre-treatment streamflow, 2006 to 2010; and (3) a before-after, control-impact analysis using precipitation and streamflow data for the pre-treatment water years 2009 and 2010. In addition, a base flow separation analysis was performed on the daily data, and seasonal base flow values were correlated to prior precipitation. Analyses were conducted at the multi-year, annual (April to March water year), and seasonal time scales. Seasons were defined as austral fall (April to June), austral winter (July to September), austral spring (October to December), and austral summer (January to March). These methods and their advantages and limitations are described below.

2.3.1. Runoff ratios and double-mass curves

Runoff ratios (Q/P, where Q = streamflow and P = precipitation) were calculated for each year and season. Double-mass curves of cumulative streamflow vs. cumulative precipitation were constructed for all study catchments for the period of record. Runoff ratios and double mass curves include both the effects of changing vegetation and changing climate.

2.3.2. Before-after analysis

A before-after analysis of streamflow was conducted following the method of Swank and Douglass (1974). The average and standard deviation of streamflow during the pre-treatment period was calculated for each catchment. The treatment effect Δ was the difference between observed streamflow in each year of the post-treatment (under restoration) period and the average pre-treatment streamflow,

$\Delta_t = Q_t - Q$ [1]

where Q_t = streamflow in period t and$Q$ = average streamflow for the pre-treatment period. The pre-treatment period was water years 2006 to 2010. For the 2006 to 2008 water years, the analysis used measured streamflow for RC5 and RC6 and daily streamflow modeled using precipitation for RC10 and RC11 (see below). The before-after comparison presumes that long-term climate (precipitation, potential evapotranspiration) is stationary.

2.3.3. Observed vs. predicted analysis

A before-after, control-impact analysis accounts for non-stationarity in climate. The treatment effect is defined as the change over time in the relationship of streamflow between a treated and a control catchment, which is assumed to have no vegetation change (Eberhardt & Thomas, 1991; Perry & Jones 2017). However, changes in vegetation over time in the control catchment significantly affect the estimated treatment effect (Jones & Post, 2004). To separate the effects of changes in precipitation from changes in vegetation, the relationship of streamflow to precipitation was estimated in each catchment for water years 2009 and 2010, the pre-treatment period when all catchments were instrumented with continuous water level sensors, and used to predict streamflow in the remaining years. The treatment effect was the difference between observed and predicted streamflow, as described below.

Daily antecedent precipitation was calculated from the complete daily precipitation record:

$AP_t = P_t + P_{t-1}{}^k$ [2]

where AP_t = antecedent precipitation on day t , P_t = precipitation on day t , and k = exponent indicating the "memory" of past precipitation events. Two values of k (0.7 and 0.9) were selected to represent relatively short ($k = 0.7$) and long ($k = 0.9$) memory.

Linear models were fitted to predict daily streamflow (Q_t) as function of daily antecedent precipitation (using two values of k) for each month during the two-year pre-treatment period:

$Q_t = \alpha + \beta\ AP_t$ [3]

This produced four models of daily precipitation (2009, 2010, each with $k = 0.7$ and $k = 0.9$) for each month of the year. Daily values of streamflow (Q_t) were estimated for all days in the period of record using each of these four models, and the average of the predicted values from the four models and its standard error was determined for each day in the record. The treatment effect, Δ , was then determined as the difference:

$\Delta = Q'_t - Q_t$ [4]

where Q'_t = observed streamflow (mm) and Q_t = predicted streamflow (mm) for each day in the record. The values of Δ were summed by year and by season.

2.3.4. Base flow separation and memory

Total daily streamflow was separated into quick flow and base flow following the method of Chapman and Maxwell (1996). Base flow was calculated as:

k 1 ? k

Qb(i) = ??? Qb (i ?1) + ??? Q(i) [5]

2 ? k 2 ? k

where Q_b = base flow (mm), Q_t = total streamflow (mm) and k is a parameter ranging between 0 and 1. Higher values of k increase the fraction of total streamflow represented by Qb. After testing different k values ranging from 0.4 to 0.97, we chose $k = 0.95$ for spring and summer and $k = 0.90$ for fall and winter, which produced stable base flow estimates.

The influence of past precipitation on streamflow in each catchment ("memory") was estimated by correlating seasonal streamflow to precipitation in the current and past seasons. The water balance for time period t is:

$Q_t = P_t - ET_t - \Delta S_t$ [6]

where Q_t = streamflow, P_t= precipitation, ET_t = evapotranspiration, and ΔS_t = change in deep soil moisture in period t . The lagged effect of prior precipitation on current streamflow is:

$Q_t = P_{t-n} - ET_{t-n} - \Delta S_{t-n}$ [7]

where Q_t is a function of P , ET , and ΔS in time period t-n , a prior season.

3. Results

3.1. Streamflow response to restoration of native forests

Predicted values of seasonal streamflow were within +/- 80 mm of observed values, and were evenly distributed as positive and negative deviations (Figure S1 a). In relative terms (i.e., %), predicted seasonal values were within +/- 40% of observed values (Figure S1 b). Changes were considered to be practically significant when they were more than 50 mm or 40% different than predicted. This level of uncertainty is comparable to confidence intervals obtained from long-term studies of paired catchments (e.g., Jones & Post, 2004; Perry & Jones, 2017).

Catchments differed substantially in the relationship of runoff to precipitation (Figure 3). Before clear-cutting, streamflow was almost two times higher per unit of precipitation at RC6 than at the contiguous catchment, RC5, with which RC6 shares a long catchment divide. Streamflow also was almost two times higher per unit of precipitation at RC11 relative to its nearby but not contiguous catchment, RC10 (Figures 1, 2 and 3). After clear-cutting, the slope of the double mass curve increased in all catchments, indicating increased streamflow (Figure 3). The greatest increase occurred at RC10, and the least at RC6, which was not clear-cut. The sum of cumulative increases at RC6 and RC5 in the post-treatment period (2011 to 2019) is similar to the increase at RC10, and higher than RC11. These observations suggest that hydrologic processes differ among the catchments, and that some portion of the flow from RC5 is transferred into RC6.

Over the entire restoration period (2011-2019), streamflow increased by 24% at RC5, 73% at RC10 and 21% at RC11, relative to the pre-treatment period (2006-2010), but precipitation changed by only 3% (Table 2). In most post-treatment years, annual streamflow increased by >200 mm after clear-cutting in most catchments, relative to predicted values based on precipitation (Figure 4). As noted above, streamflow in RC6 increased immediately after the clear-cut, whereas streamflow did not increase at RC5 until the second year after the clear-cut. (Table 2, Table S2).

Seasonal streamflow response in absolute terms (mm) in the three catchments under restoration was greatest in winter, followed by fall, spring, and summer, based on the before-after method (Figure 5, Figure S2). Seasonal streamflow increased by more than 300 mm (16 to 31% of pre-treatment annual streamflow) in all three catchments only in winter of 2014 (Table 2, Table S2). Streamflow response based on predicted streamflow relative to 2009 and 2010 (%) was greatest in summer and fall, and smaller in winter and spring (Figure 6). Streamflow increased by more than 150% relative to pre-treatment in fall and summer of some years at RC5, RC10, and RC11. Streamflow increased by more than 50% in all four seasons at RC5 and RC10 in most post-treatment years. Some differences were apparent in streamflow responses relative to the 2006 to 2010 pre-treatment period compared to those relative to the 2009 and 2010 pre-treatment period. The 2006 to 2010 pre-treatment period included 2006 to 2008, when streamflow was estimated manually once a day, or from regression relationships with precipitation, and years with high and low precipitation. In contrast, the 2009 to 2010 pre-treatment period included years with consistent automated measurements of streamflow, and years with average precipitation relative to the study period.

3.2. Vegetation recovery in catchments under restoration

Vegetation cover of non-tree species from natural regeneration increased rapidly after clear-cutting and planting of *Nothofagus* seedlings in RC5, RC10, and RC11. Non-tree vegetation cover reached a maximum of 63 to 106% between 2012 and 2016, one to five years after restoration began, and then declined in 2020 as cover of planted and naturally regenerated tree species increased (Table S3, Figure S3). Cover of non-tree species and survival of planted trees was lowest in RC5, where*Eucalyptus* stumps sprouted vigorously, compared to RC10 and RC11, where *Eucalyptus* sprouting was prevented by application of herbicide (glyphosate) to cut stumps. *Eucalyptus* recruitment from seeds occurred in all three catchments (Figure S3, Table 3).

By 2020, vegetation cover of tree species ranged from 48% (RC5) to 78 % (RC10) (Table 3). The density of surviving *N. dombeyi* saplings planted in 2011 was lower in RC5 (43%) compared to RC10 (90%) or RC11 (73%). The density of saplings and seedlings of naturally regenerated native tree species was thirty times higher than that of the planted species, *N. dombeyi* (Table 3, Table S4). Over the period 2012 to 2020, densities of saplings of native tree species increased in all three catchments, and densities of *Eucalyptus* saplings declined in RC10 and RC11 (Figure S3). In 2020, total basal area of planted*N. dombeyi* and naturally regenerated trees was much lower in RC5 (2.3 m^2/ha) than in RC10 (9 m^2/ha) or RC11 (9.8 m^2/ha) (Table 3). In contrast, basal area of *Eucalyptus* trees that seeded in or sprouted from cut stumps was greater in RC5 than in RC10 or RC11 (Table 3). From 2010 to 2020, basal area of the *Eucalyptus* plantation in RC6 increased from 38 to 61 m^2/ha (Table 1). By 2020, basal area of trees in the portion of the catchments under restoration was 16 to 20% of native forest basal area in the riparian zones and 12 to 18% of the basal area in the untreated *Eucalyptus* plantation in RC6 (Figure 1, Table 3).

3.3. Factors affecting streamflow response: precipitation variability, catchment hydrology, native vegetation recovery

Streamflow response varied with precipitation, vegetation development, catchment hydrology, and their interactions. Seasonal precipitation varied during the study period (CV 0.2 to 0.41 for 2006-2019, Table 4). Annual precipitation was lowest in water years 2007 and 2016 and highest in water years 2006 and 2012. Summer precipitation was lowest in 2006 and 2014 (Table 4). Runoff ratios were positively related to precipitation among years and among seasons (Figure S4). The largest increases in streamflow during the restoration period occurred in the winter of 2014 (Figure 5, Figure 6, Figure S2), after unusually high fall and winter precipitation (Table 4). The largest post-harvest streamflow deficits occurred in 2016 (Figure 5, Figure 6, Figure S2), when precipitation was very low (Table 4).

Base flow on average over the study period accounted for 42 to 45% of total flow in fall, 50% in winter, and 52 to 54% in spring in all catchments, with little variation among years (Figure S5). Average summer base flow was lower at RC5 and RC10 (base flow 37 to 41% of total) compared to RC6 and RC11 (50 to 53%) (Figure S5).

Summer base flow was consistently lower and more variable at RC5 and RC10 than at RC6 or RC11. During a series of years with comparatively low precipitation in spring and summer (2014 to 2016, Table 4), summer base flow declined steadily in RC5 and RC10, but it recovered by the end of the 2016 water year (i.e., January to March of 2017, Figure 7). In contrast, summer base flow remained constant in all years at RC11, except at the end of water year 2014, when it declined abruptly for one year. Base flow was consistently high in all years in RC6.

Base flow was significantly positively related to precipitation in the same season in fall, winter, and spring at all catchments. Summer base flow was significantly positively related to spring precipitation in RC5 and RC6; these were the only significant lagged responses of base flow to prior precipitation (Figure 8).

Base flow increased by 28 to 87% in the catchments under restoration for the period 2011 to 2019 compared to the pre-treatment period (Table 5). Annual base flow as a percentage of total flow was consistently higher than the long term mean in 2017 to 2019 at all catchments, despite below-average annual precipitation in 2018 and 2019 (Figure 9). Increasing base flow trends are most evident in winter, spring, and summer (Figure S6).

Streamflow increases were consistently high during the restoration period in RC10 (Figure 3, Figure 4, Figure 5, Figure 6), which had the highest survival of planted *Nothofagus* , highest density of other native saplings and seedlings, absence of *Eucalyptus* saplings or trees, and highest percentage of the catchment covered by the riparian buffer (Table 1, Table 3, Figure S3).

4. Discussion

A growing body of literature attributes reductions in streamflow in South America to intensive plantation forestry using non-native species (Alvarez-Garreton, Lara, Boisier, & Galleguillos, 2019; Ferraz, Lima, & Rodrigues, 2013, 2019; Garcia, Salemi, Lima, & Ferraz, 2018; Huber, Iroumé, & Bathurst, 2008; Lara et al., 2009; Little, 2009, 2014). In North America, evidence is accumulating that intensively managed plantations of native species can reduce streamflow (Gronsdahl, Moore, Rosenfeld, McCleary, & Winkler, 2019; Perry & Jones, 2017; Segura et al., 2020). Drought and climate change can exacerbate these reductions (Crampe, Segura, & Jones, in review; Iroumé et al., in review).

Consistent with studies in other locations, post-clear-cutting increases in streamflow in absolute terms (mm) were highest and more consistent from year to year in fall and winter, and absolute increases were low and inconsistent in spring and summer. However, increases in streamflow in relative terms (%) were highest in the fall and summer, although summer streamflow was reduced in dry summers (2014-2015). Base flow increased gradually over the restoration period. The pre-treatment runoff ratios in the study catchments were on the high end of rates reported from *Eucalyptus* and other exotic forest plantations in south-central Chile and Brazil (e.g. Huber et al., 2008; Ferraz, Rodrigues, Garcia, Alvares, & Lima, 2019; Iroumé et al., 2020). If the study catchments had been replanted with *Eucalyptus* , we would have expected a reduction in streamflow within one to three years after the post-clear-cutting increase in streamflow, but under regenerating native forests, streamflow increased, and over the longer term, base flow also increased relative to conditions under the former *Eucalyptus* plantations. These findings indicate that the former *Eucalyptus* plantations had depleted soil moisture reservoirs in the study catchments. Clear-cutting of *Eucalyptus* , its replacement with *Nothofagus* native trees, and natural regeneration of other tree species appear to have reduced transpiration, increased soil moisture storage, and increased streamflow, except during some dry periods.

Multiple findings, including different runoff ratios and base flow responses among catchments, delayed responses of base flow to restoration, and increased streamflow in an untreated catchment which was adjacent to a clear-cut, indicate that the streams are fed in part by delayed subsurface flow. Groundwater flows as deep as 6-8 meters under saturated soil conditions in winter can be observed on road cuts in the study area. Dipping bedding planes of the underlying metamorphic rocks, which are steeper than the hillslope gradients, appear to convey subsurface flow among these small catchments. This delayed flow is an important contributor to base flow, especially during summer.

Relative increases in streamflow after clear-cutting were highest at the two catchments which had the lowest runoff ratios and where summer base flow fluctuated the most in response to seasonal and inter-annual variation in precipitation (RC5 and RC10, Table S2). Both absolute and relative responses were lower at the catchment which had the highest runoff ratio and where summer base flow was insensitive to variation in precipitation. In other words, catchments with limited streamflow contributions from delayed flow were more responsive to restoration than those with sustained base flow. These findings are consistent with other studies showing that catchment hydrology can moderate streamflow response to change in vegetation and climate (Spencer, Anderson, Silins, & Collins, 2020; Tague, Valentine, & Kotchen, 2008; Vose et al., 2016).

Streamflow increased following clear-cutting of *Eucalyptus* plantations and regrowth of planted native *Nothofagus* trees and naturally regenerated native forest species over the restoration period. The gradual recovery of annual base flow through the nine-year period of restoration, and the pronounced increase in base flow during the last three years of the study, despite low precipitation in the last two years of the study, imply that native forest restoration has the potential to restore deep soil moisture reservoirs that sustain base flow during dry periods, and therefore may enhance the resilience of restored catchments to drought.

The immediate post clear-cutting increase in streamflow in RC6 (a *Eucalyptus* plantation that was not clear-cut), the delayed response of streamflow at the adjacent clear-cut catchment RC5, and the higher runoff ratio at RC6 compared to RC5 (Figures 3 and 4) indicate that flow is transferred from RC5 to RC6. Yet despite the streamflow subsidies from RC5, base flow at RC6 remained low from 2017 through 2019, whereas it increased in all the catchments under restoration (Figure 9). In addition, the highest correlation between summer streamflow and spring precipitation occurred at RC6. These findings indicate that high evapotranspiration rates of the prior *Eucalyptus* plantations had depleted deep soil moisture reservoirs, which recovered, and restored base flow in restored catchments over the period of study. The *Eucalyptus* plantation aged from 7 to 20 years over the course of the study, whereas typical rotations in these plantations are 12-15 years. The plantation continued to grow and nearly doubled in basal area from 2010 to 2020 (Table 3). Thus, in contrast to the finding that water use by *Eucalyptus* is reduced in older plantations globally (Farley et al., 2005), this study indicates that aging *Eucalyptus* plantations continue to evapotranspire at high rates that prevent recharge of deep soil moisture reserves.

The relatively high and persistent streamflow increases in catchment RC10 (Figure 3, Figure 4, Figure 5, Figure 6) may in part be due to native forest restoration in this catchment, which had the highest survival of planted *Nothofagus* , highest density of other native saplings and seedlings, and no *Eucalyptus* saplings or trees (Table 3). However, despite similar forest restoration outcomes at RC10 and RC11, streamflow increased much less at RC11 than at RC10 during the period of restoration (Table 2, Table 3). Nevertheless, the substantially higher base flow at RC11 in 2016 to 2019 relative to before clear-cutting (Figure 7, Figure 9) implies that native forest restoration may have contributed to increased base flow even in RC11, which had the highest runoff ratio of all study catchments (Figure 3, Figure S4). Our results do not show a clear effect of the native forest riparian buffer (width and percentage of the catchment covered) on streamflow as reported earlier for this study site (Little et al., 2014).

The magnitude of streamflow response in this long-term experiment is roughly consistent with the streamflow responses modeled by Alvarez-Garretón et al. (2019), who estimated 40% reductions in streamflow in catchments with intensively managed fast-growing plantations, relative to native forest. In addition to restoring the hydrologic regime, forest restoration with native tree species also can contribute to carbon sequestration for climate change mitigation efforts (Bastin et al., 2019; Lewis, Wheeler, Mitchard, & Koch, 2019). Results from this study indicate that the restoration of native forests might increase carbon sequestration for climate regulation and at the same time improve water provision, two crucial ecosystem services. This study reinforces the tight coupling between forest management, water, and carbon, and their relationship to Sustainable Development Goals (e.g., Creed et al., 2019). The findings from this study may inform policy to address trade-offs between carbon sequestration and water yield, relevant to the National Determined Contributions of Chile within the United Nations Framework Convention on Climate Change.

This study also indicates that native forest restoration in areas of former exotic forest plantations may enhance the resilience of streamflow to climate drying in southern Chile. The study occurred during an unprecedented mega-drought (2010 to present), although precipitation records at the site do not show clear downward trends. Climate models project continued drying trends throughout the present century (Boisier, Rondanelli, Garreaud, & Muñoz, 2016; Bozkurt, Rojas, Boisier, & Valdivieso, 2018; Garreaud et al., 2017). Hence, there is a need for continued studies, such as this one, of forest management to enhance streamflow resilience to drought. A broader suite of experiments is needed to examine how native forest restoration affects water yield along a precipitation gradient in South America. Ideally, a long-term study program would consider the effects of different former forest plantation species (*e.g. Eucalyptus, Pinus*), stand density and age, and soil type, as well as native forest composition, density and diversity along this climatic gradient.

5. Conclusions

This study demonstrated how native forest restoration in former*Eucalyptus* plantations affected streamflow over a nine-year post-treatment period in the Valdivian Coastal Reserve, south-central Chile. To our knowledge this study is the first to test streamflow response to native forest restoration in former fast-growing*Eucalyptus* forest plantations. Clear-cutting of *Eucalyptus*plantations and replacement with young planted and naturally regenerating native forest species increased streamflow and enhanced water provision, a key ecosystem service. An aging *Eucalyptus*plantation (7 to 20 years) continued to have high rates of transpiration that apparently prevented the recovery of base flow, whereas base flow gradually increased in the catchments under restoration, confirming predictions that native forest has lower evapotranspiration rates than intensively managed fast-growing plantations. A very dry year, early in the restoration period, revealed that the catchments were still prone to drought-induced streamflow reductions, whereas later increases in base flow indicated that restoration of base flow after removal of forest plantations may require a decade or more.

This catchment forest restoration study is a long-term effort. The native forests under restoration are very young (8 years old) and will continue to change and affect streamflow as they grow. The development of a fully stocked, multi-tier forest is expected to take 50 to 70 years, and conditions comparable to old-growth Valdivian rainforest will require 130 to 180 or more years (Lara et al., 2013). Continued monitoring of these experimental catchments is essential to understand how native forest succession influences streamflow in the long term.

Differences in streamflow response among catchments under restoration of native forests could not be attributed to specific differences in native stand density or basal area, nor to differences in the area in native forest riparian buffers. Instead, other factors controlling catchment hydrology, such as geomorphology and geology that determined water transfer and differences in groundwater storage capacity, influenced streamflow response to forest restoration.

This long-term forest hydrology research and monitoring program has been possible due to a diverse institutional arrangement involving academic, NGO, and forest industry partners, and a sequence of grants from various agencies throughout this period. Maintaining long-term catchment studies is a major challenge in

Chile, which like many countries in Latin America lacks a national funding program for long-term catchment or ecosystem research. The basic research findings about hydrology and forest succession and their relevance to key policy decisions about water and forest ecosystems in the context of climate change, as shown by this study, underscore the importance of continuation and expansion of long-term catchment forest hydrology studies in Chile and elsewhere in the global South.

6. Data Availability

All the datasets generated and analyzed for this study will be available at:

http://www.cr2.cl/datos-cuencas-restauracion-reservavaldiviana/

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Tables

Table 1. Characteristics of the study catchments. At the beginning of the study (2006), all catchments were covered by *Eucalyptus*plantations established in 1999. Pre-clear-cutting values for*Eucalyptus* height, dbh, and basal area are based on four plots inventoried by Masisa S.A. (Víctor Guerrero, personal communication). Height estimates for *Eucalyptus* in 2020 are based on models from Masisa S.A. (Jorge Echeverría, personal communication).

Catchment name	RC5	RC6	RC10	RC11
Area (ha)	3.74	5.26	3.43	4.28
Harvest date	Apr 2011	–	Feb-Apr 2011	Feb-Apr 2011
Elevation (m)	6 to 107	6 to 124	116 to 164	115 to 195
Mean slope (%)	46.6	45.2	41	42.7
Buffer width	29.6	29.2	45	34.4
Buffer area (%)	23.9	30.6	36.9	25.3
% cover *Eucalyptus* (2006-2010)	76.1	69.4	63.1	74.8
Eucalyptus, prior to clear-cutting				
Mean height (m)	22.4	17.9	15	17.8
Mean diameter at breast height (cm)	19.1	12	20	15.2
Basal area (m^2/ha)	60.2	37.8	63.0	47.9
Eucalyptus, 2020				
Mean height (m)	–	25.9	–	–
Mean diameter at breast height (cm)	–	20.9	–	–
Basal area (m^2/ha)	4.7	60.7	–	1.3

Table 2. Annual (water year) streamflow and precipitation (mm) in the four study catchments, and percent difference (% diff) for each year relative to the pre-treatment mean (2006-2010). The bottom row shows percent change for the period of restoration (2011-2019) relative to the pre-treatment water years 2009 to 2010, when automated gage records began.

	RC5	RC5	RC6	RC6	RC10	RC10	RC11	RC11	Precipitation	Prec
Year	mm	% diff	mm	% diff	mm	% diff	mm	% diff	mm	% di
2006	1374	42	1469	6	1146	17	2299	24	3148	28
2007	739	-23	943	-32	701	-28	1304	-30	1558	-37
2008	1329	38	1530	10	1034	6	1885	2	2427	-1
2009	793	-18	1526	10	1097	12	1923	4	2804	14
2010	590	-39	1464	6	901	-8	1873	1	2347	-4
2011	714	-26	1808	30	1961	101	2540	37	2694	10
2012	1371	42	1855	34	2168	122	2853	54	2806	14
2013	1120	16	1892	36	1767	81	2361	27	2603	6
2014	2088	116	2160	56	1845	89	2274	22	2725	11
2015	1168	21	1799	30	1582	62	2107	13	2554	4
2016	771	-20	1090	-21	870	-11	1565	-16	1977	-20
2017	1605	66	2292	65	2138	119	2565	38	2916	19
2018	1200	24	2050	48	1616	66	2114	14	2385	-3
2019	756	-22	1677	21	1291	32	1866	0	2144	-13
Ave, 2006-10	965		1386		976		1857		2457	
Ave, 2009-10	692		1495		999		1898		2576	
Ave, 2011-19	1199		1847		1693		2249		2534	
% change, 2011-2019 vs. 2006-2010	24		33		73		21		3	

	RC5	RC5	RC6	RC6	RC10	RC10	RC11	RC11	Precipitation	Prec
% change, 2011-2019 vs. 2009-2010	73		24		69		18		-2	

Table 3. Percent cover, density of seedlings, saplings, and adult trees, and basal area in 2020 in the clear-cut and planted catchments. Buffer = native forest riparian buffer. Other native tree species are naturally regenerated (listed in Table S1). N=4 plots in the planted area, 1 in the buffer. Seedlings were [?] 2 m in height; saplings were >2 m in height and <5 cm dbh; trees were> 5 cm dbh. Survival (%) of *N. dombeyi*expressed as number of saplings + trees in relation to the mean initial plantation density (1500 seedlings/ha).

	RC5	RC5	RC10	RC10	RC11	RC11
	Planted area	Buffer	Planted area	Buffer	Planted area	Buffer
Vegetation cover (%)						
Non-tree species	50	61	37	51	83	95
Tree species	48	100	78	98	64	100
Seedling density (N/ha)						
Eucalyptus	0	0	0	0	0	0
Native species	7166	82484	9077	5414	1911	13057
N of species	8	10	12	4	6	9
Sapling density (N/ha)						
Eucalyptus	40	0	0	0	0	0
All native species	7340	6320	8720	5040	7120	4160
Nothofagus dombeyi	260	0	280	0	240	0
Other native species	7080	6320	8440	5040	6880	4160
N of species	11	10	12	11	9	10
Tree density (N/ha)						
Eucalyptus	290	0	0	0	40	0
All native trees	500	3080	1350	2880	1180	1640
Nothofagus dombeyi	390	0	1080	0	860	0
Other native species	110	3080	270	2880	320	1640
N of species	6	8	5	12	8	11
Saplings+trees (N/ha)						
Nothofagus dombeyi	650	0	1360	0	1100	0
N. dombeyi survival (%)	43		91		73	
Basal area (m^2/ha)						
Eucalyptus	4.7	0	0.0	0	1.3	0
All native trees	2.3	38.4	9.0	45.8	9.8	67.7
Nothofagus dombeyi	2.0	0	8.2	0	8.6	0
Other native species	0.4	38.4	0.9	45.8	1.1	67.7
Total basal area	7.1	38.4	9.0	45.8	11.0	67.7

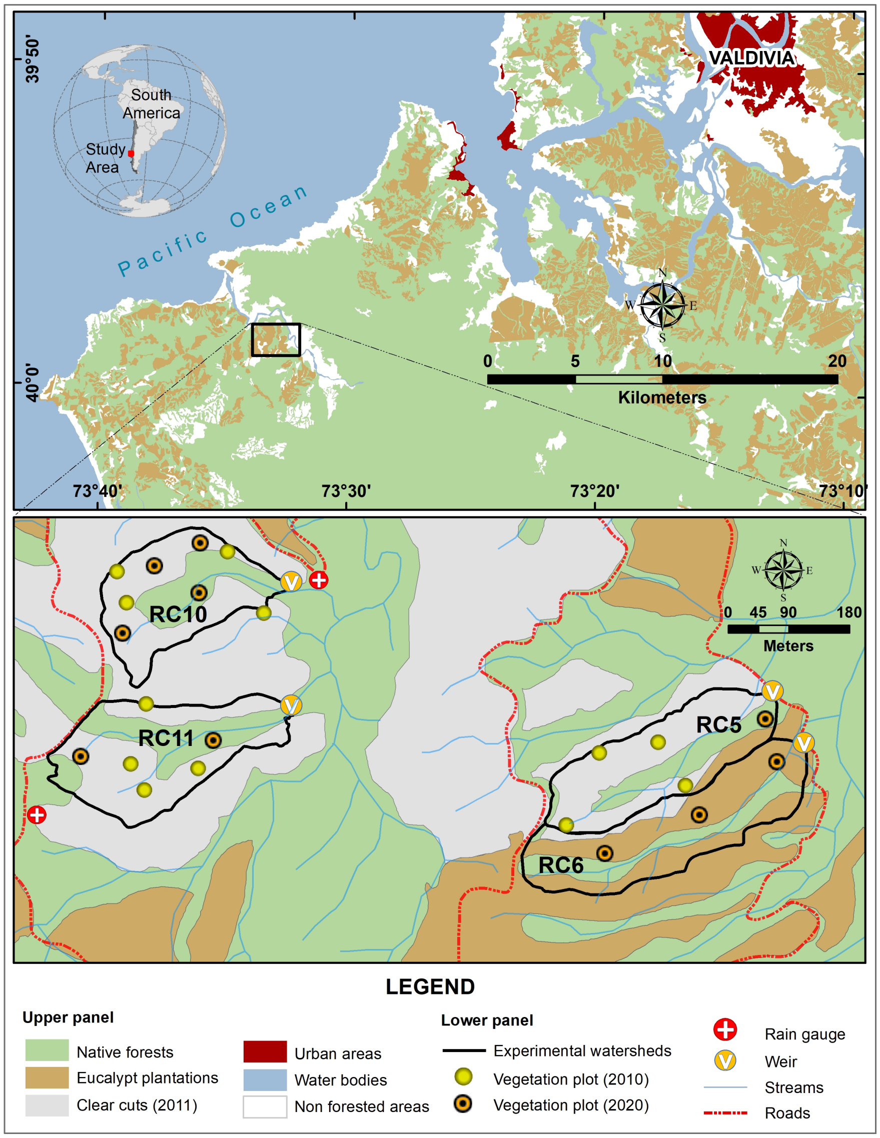
Table 4. Precipitation by season and water year (April 1 to March 31).

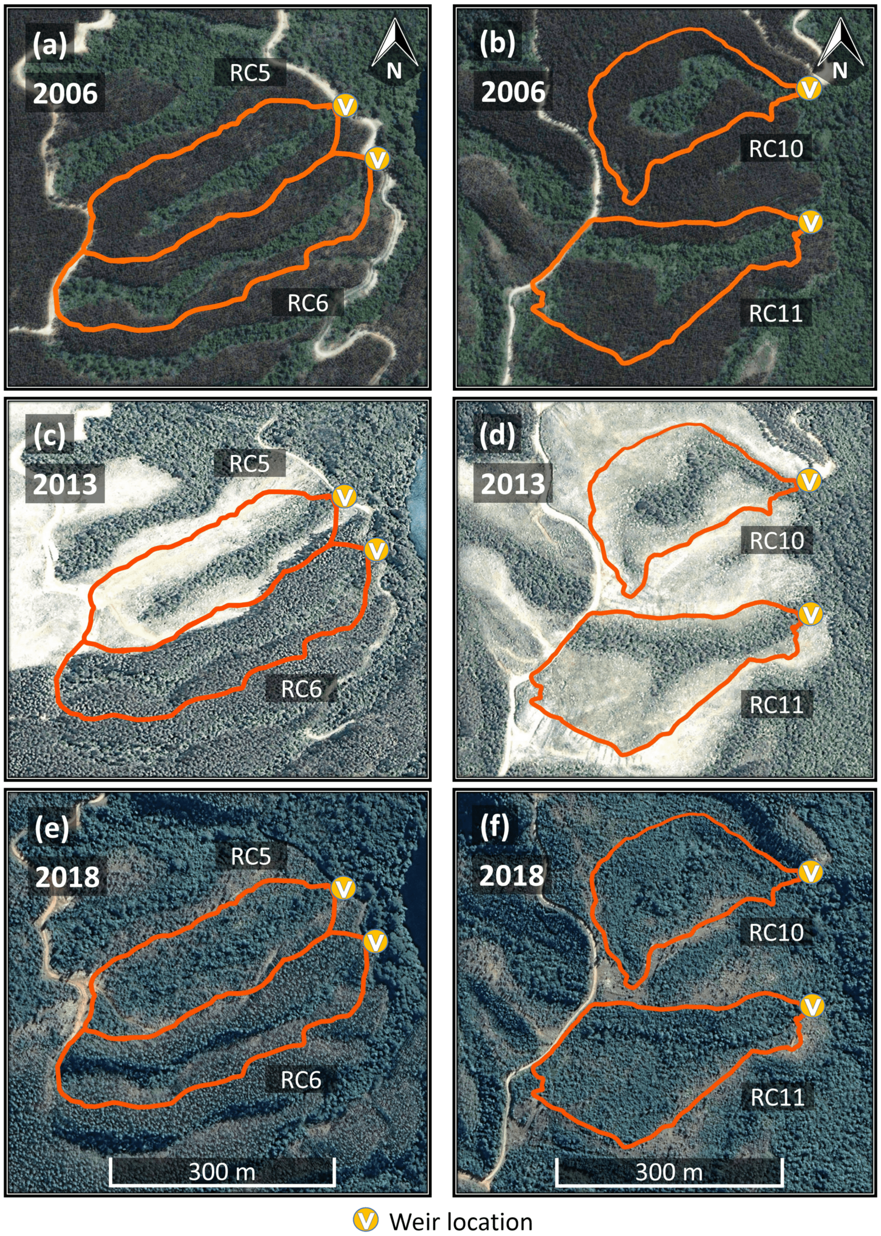
Year	Annual (Apr-Mar)	Fall (Apr - Jun)	Winter (Jul - Sep)	Spring (Oct - Dec)	Summer (Jan - Mar)
2006	3148	1478	994	473	203
2007	1558	498	557	317	186
2008	2427	823	1184	200	220

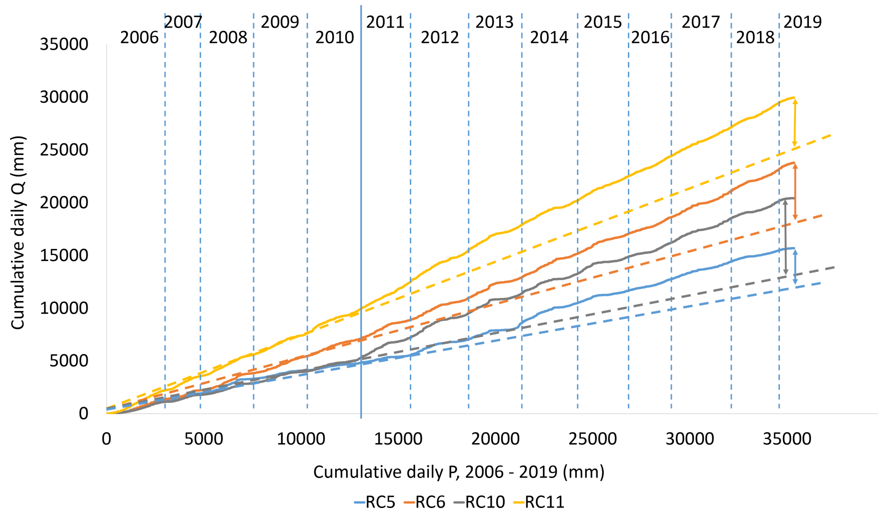
Year	Annual (Apr-Mar)	Fall (Apr - Jun)	Winter (Jul - Sep)	Spring (Oct - Dec)	Summer (Jan - Mar)
2009	2804	901	840	654	409
2010	2347	767	776	463	342
2011	2694	836	1147	289	422
2012	2806	1017	970	552	267
2013	2603	983	874	327	419
2014	2725	1040	1209	364	112
2015	2554	854	1078	398	224
2016	1977	373	715	563	326
2017	2916	906	987	639	384
2018	2385	801	942	483	160
2019	2144	824	820	367	133
average	2506	864	935	435	272
SD	412	254	187	135	110
CV	0.16	0.29	0.20	0.31	0.41
%	100	34	37	17	11
min	1558	373	557	200	112
max	3148	1478	1209	654	422
range	1591	1105	652	454	310
% of mean	63	128	70	104	114

Table 5. Mean monthly base flow (mm) and precipitation (mm) for the period of study, and before and after clear-cutting and planting of native forest in RC5, RC10, and RC11.

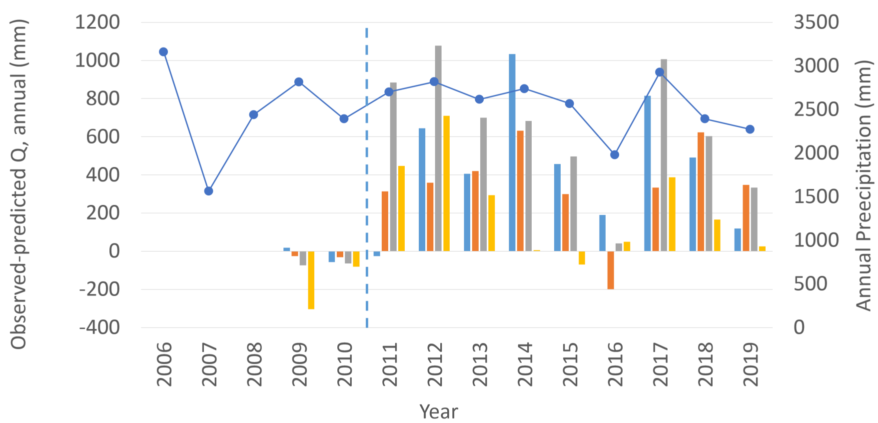
	RC5	RC6	RC10	RC11	Precipitation
2006-2019					
mean	46	72	59	85	211
SD	52	58	65	70	143
CV	1.1	0.8	1.1	0.8	0.7
2006-2010					
mean	39	58	38	71	206
SD	45	49	41	65	156
CV	1.2	0.8	1.1	0.9	0.8
2009-2010					
mean	28	65	39	72	215
SD	23	38	40	60	124
CV	0.8	0.6	1.0	0.8	0.6
2011-2019					
mean	50	80	71	93	214
SD	55	61	73	72	136
CV	1.1	0.8	1.0	0.8	0.6
% change, 2011-2019 vs. 2006-2010	28	38	87	31	4
% change, 2011-2019 vs. 2009-2010	79	23	82	29	-1


39°50'
40°0'
South
America
Study
Area
Pacific Ocean
VALDIVIA
N
W
E
S
0
5
10
20
Kilometers
73°40'
73°30'
73°20'
73°10'
RC10
RC11
RC5
RC6
0
45
90
180
Meters
LEGEND
Upper panel
Native forests
Eucalypt plantations
Clear cuts (2011)
Urban areas
Water bodies
Non forested areas
Lower panel
Experimental watersheds
Vegetation plot (2010)
Vegetation plot (2020)
Rain gauge
Weir
Streams
Roads

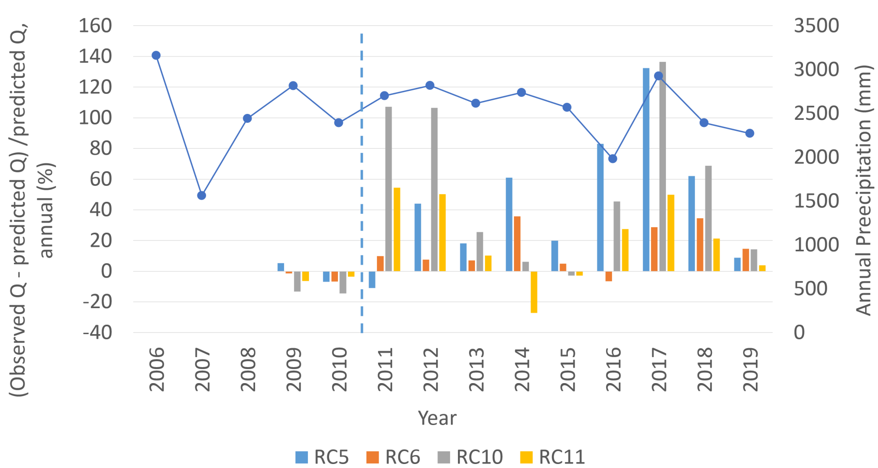

(a)
2006
RC5
RC6
N
(b)
2006
RC10
RC11
N
(c)
2013
RC5
RC6
(d)
2013
RC10
RC11
(e)
2018
RC5
RC6
300 m
(f)
2018
RC10
RC11
300 m
Weir location

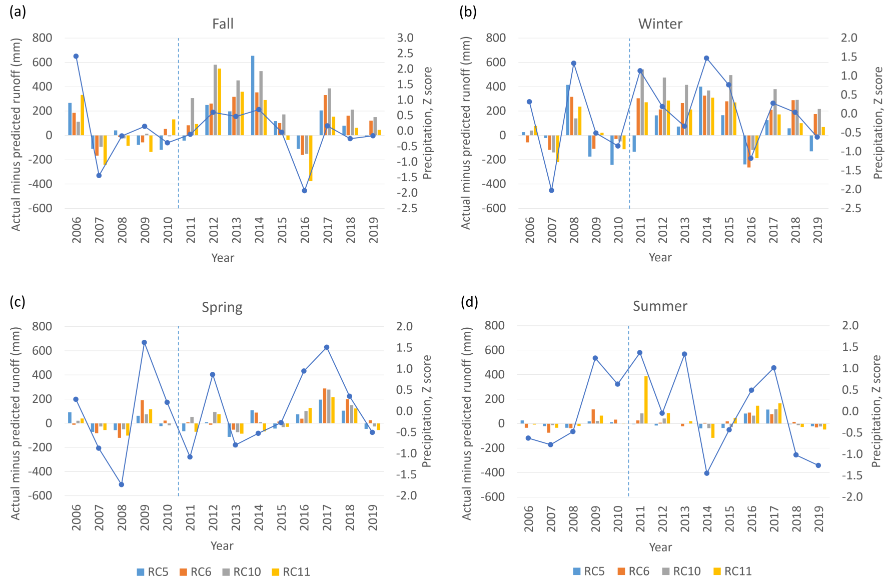

Cumulative daily Q (mm)
Cumulative daily P, 2006 - 2019 (mm)
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
RC5
RC6
RC10
RC11

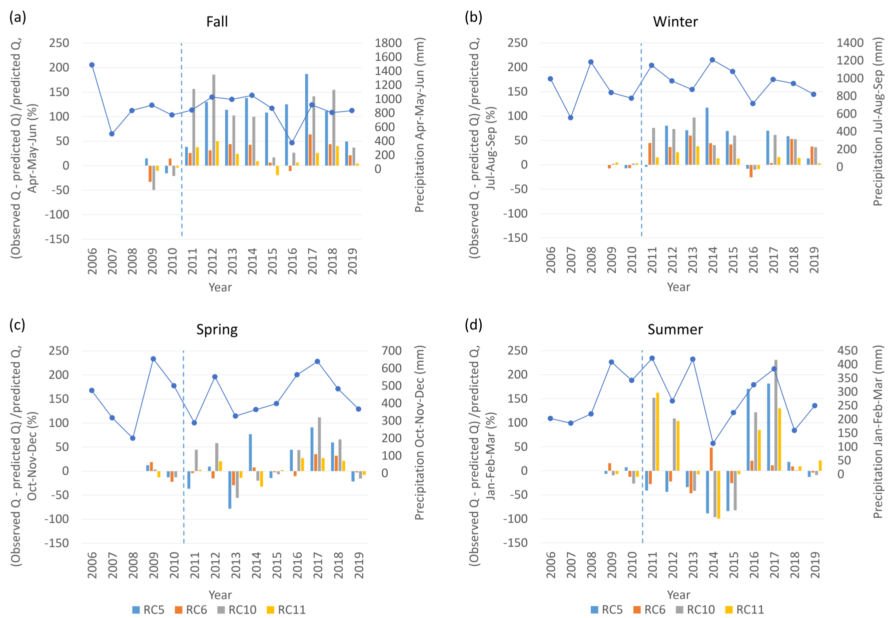
(a)

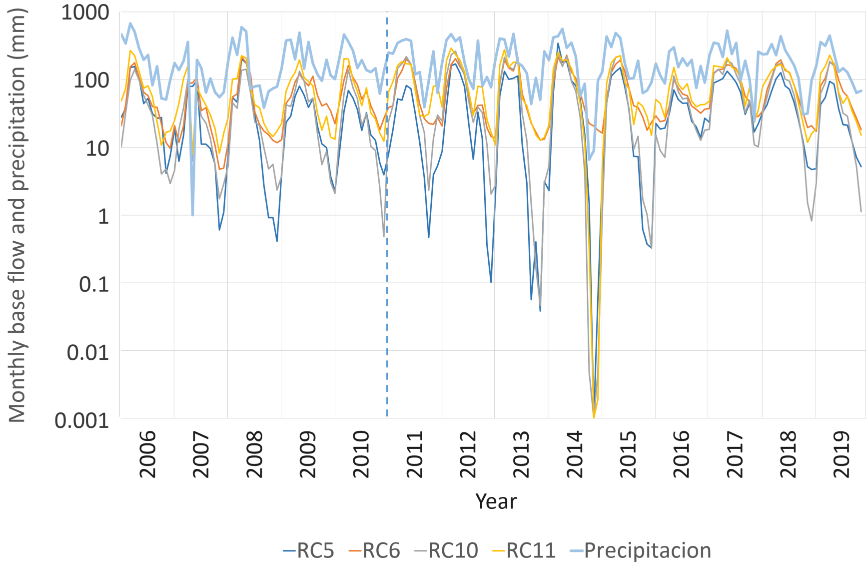

Observed-predicted Q, annual (mm)
Annual Preecipitation (mm)
Year

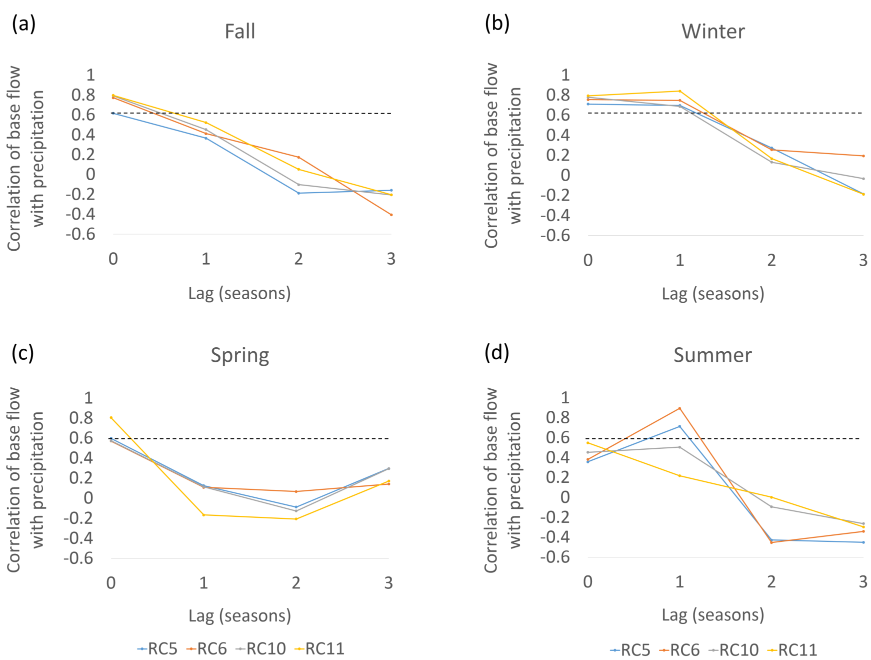
(b)

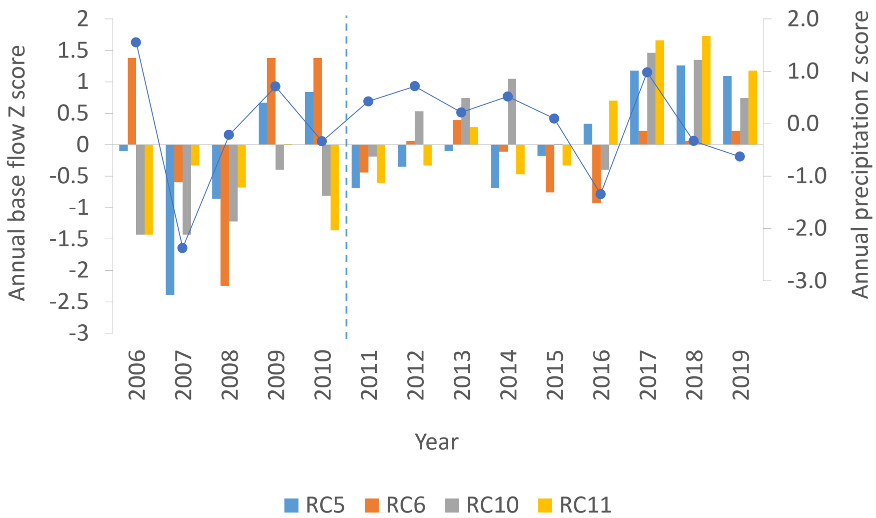

(Observed Q - predicted Q) /predicted Q, annual (%)
Annual Preecipitation (mm)
Year
RC5
RC6
RC10
RC11


(a)
Fall
(b)
Winter
(c)
Spring
(d)
Summer
Actual minus predicted runoff (mm)
Precipitation, Z score
Year
RC5
RC6
RC10
RC11


(a)
Fall
(Observed Q - predicted Q) /predicted Q, Apr-May-Jun (%)
Precipitation Apr-May-Jun (mm)
(b)
Winter
(Observed Q - predicted Q) /predicted Q, Jul-Aug-Sep (%)
Precipitation Jul-Aug-Sep (mm)
(c)
Spring
(Observed Q - predicted Q) /predicted Q, Oct-Nov-Dec (%)
Precipitation Oct-Nov-Dec (mm)
(d)
Summer
(Observed Q - predicted Q) /predicted Q, Jan-Feb-Mar (%)
Precipitation Jan-Feb-Mar (mm)
Year
RC5
RC6
RC10
RC11


Monthly base flow and precipitation (mm)
1000
100
10
1
0.1
0.01
0.001
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year
RC5
RC6
RC10
RC11
Precipitacion


(a)
Fall
(b)
Winter
(c)
Spring
(d)
Summer
Correlation of base flow with precipitation
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
1
2
3
Lag (seasons)
RC5
RC6
RC10
RC11


Annual base flow Z score
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
Annual precipitation Z score
2.0
1.0
0.0
-1.0
-2.0
-3.0
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
Year
RC5
RC6
RC10
RC11