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ORIGIINAL ARTICLE

The potential use of tree-rings to reconstruct streamflow and estuarine salinity in the Valdivian Rainforest eco-region, Chile

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Abstract

Water availability is one of the main limitations for future development and economic activity in many regions of the world. This applies even to areas of relatively high annual rainfall, such as the Valdivian Rainforest eco-region in Chile (35–48°S). Streamflow and water availability are crucial for several economic activities in the eco-region including hydroelectricity, irrigation, salmon farming, sports fishing of introduced trout and tourism. Scientific research focused on the spatial and temporal patterns of streamflow is a key element for planning the future development within the eco-region. In this paper we explore the potential of tree-rings for streamflow reconstruction in this region. Our preliminary results indicate a significant correlation ($r = 0.59$ $P < 0.001$, 1929–2000) between prior summer Río Bueno streamflow (January–April) and the average between a composite tree-ring chronology using *Pilgerodendron uviferum* from Chile and two composite *Austrocedrus chilensis* chronologies from Argentinean Patagonia. Similarly, there is a significant correlation ($r = 0.57$, $P < 0.001$, 1943–2002), between the *Austrocedrus* chronology (40°44′S) at Centinela in Argentinean Patagonia and the previous spring through early autumn (November–April) streamflow for Río Puelo. The tree-ring records used to correlate with Río Bueno and Río Puelo discharges show low-frequency variability and therefore the potential to reconstruct this variability in streamflow for the last 500–780 years. We also found a significant correlation between the composite *Pilgerodendron* standard ring-width chronology and the current summer water salinity (January–April) at the Reloncavi Estuary ($r^2 = 0.60$, $P < 0.01$, 1992–2000). Water salinity is a crucial determinant of the carrying capacity of salmon farming. Future research should provide reconstructions of streamflow, water salinity and other water quality attributes from tree-rings. These data will provide inputs to modeling scenarios of future water availability and are crucial to decision-making and planning of resource management and socio-economic development in the Valdivian Rainforest eco-region.

Keywords: Ecosystemic services; Water resources; Patagonia

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Introduction

Water availability is one of the main limitations for future development and economic activity in many regions of the world (Arnell et al., 2001; Viviroli et al., 2003). This applies not only to the arid and semi-arid regions but also to areas of high rainfall and excellent water quality such as the Valdivian Rainforest eco-region in Chile (35–48°S) and adjacent Argentina. The eco-region in Chile covers 27 million hectares with diverse climatic regimes, land-use and forest types (Dinerstein et al., 1995; Lara et al., 2003). Climate varies from mediterranean-type in the north (35–38°S), with 3–4 dry summer months (December–March) to rainy temperate climates south of 40°S (Miller, 1976; Pezoa, 2003). Data concerning the spatial and temporal patterns of streamflow are key to planning future development within the eco-region that would enhance the quality of life and economic opportunities. Streamflow and water availability are crucial for hydroelectricity (50% of total electrical production in Chile is concentrated in the northern portion of the eco-region) and for irrigation in the drier area between 35° and 38°S (Lara et al., 2003). Water is also vital for salmon farming (over 80% of the value of exports from the Lake Region), sports fishing of introduced trout and tourism in the southern portion of this region (40–48°S; Soto and Lara, 2001; Lara et al., 2003).

Most of the watersheds in the eco-region have rainfed or mixed nival/rainfall regimes and streamflow is primarily controlled by precipitation inputs (Niemeyer and Cereceda, 1984). Therefore, understanding streamflow variability demands knowledge of the climatic controls of precipitation variability at all timescales. In addition to these natural controls of streamflow, recent research has demonstrated that streamflow is greatly influenced by land use and forest cover. Preliminary flow data over two summers in 10 watersheds indicate that streamflow/ha for December through March in watersheds covered by adult *Pinus radiata* (D. Don) (Monterrey Pine) plantations is less than 5% of comparable watersheds covered by native forests (Oyarzún et al., submitted for publication). This is due to the higher evapotranspiration rate of pine plantations compared to native forests.

Problems of water supply from wells, springs and streams are frequently reported during the summers in many rural areas that have been converted from native forests to forest plantations, or to a mosaic of plantations, agriculture and pastureland (Lara et al., 2003). In the north (38–41°S) these problems are especially critical during the episodic summer droughts associated with El Niño/ENSO events (Aceituno, 1988; Montecinos and Aceituno, 2003). Problems in water availability have been intensified by an increase in water demand in recent decades (Lara et al., 2003).

In this paper we describe examples of the potential application of tree-rings to the reconstruction of streamflow in the Valdivian Rainforest eco-region of Chile. We also briefly explore possible relationships between tree-rings and estuarine salinity in this region.

How can dendrochronology address these problems?

Most instrumental records for streamflow and precipitation in the Valdivian Rainforest eco-region start after 1930. The shortness of these records severely restricts the development of adequate and reliable predictions of streamflow. This limitation is underscored by the fact that the variability and frequency of extreme events during the 20th century has globally increased (Karl and Easterling, 1999; Easterling et al., 2000).

Tree-ring records provide continuous, annually resolved series of past environmental changes that can usually provide proxy records of several centuries and in some cases, millennia. Long reconstructions can be developed by correlating tree-growth records with discharge in unregulated rivers (natural flow) and the characteristic variability analyzed at several frequencies. These streamflow reconstructions have proved valuable in hydrologic studies in semi-arid regions in North America (e.g. Stockton and Jacoby, 1976; Meko et al., 1995, Hidalgo et al., 2000; Woodhouse, 2001; Brito-Castillo et al., 2003). In the southwestern United States, the Colorado River has been intensively studied because of its importance as a water source for seven US states and Mexico. This research has demonstrated that the decisions on international water allocations were made during a period of exceptionally high flows that have led to considerable hardship and subsequent controversy which might have been avoided had longer records (e.g. from tree-rings) been available (Stockton and Jacoby, 1976).

Despite the potential of tree-ring records to provide streamflow reconstructions, few have been carried out in South America, all of them in Argentina. Holmes et al. (1979) used tree-ring indices of *Araucaria araucana* (Molina) K. Koch. (Araucaria or Pehuen) and *Austrocedrus chilensis* (D. Don) Florín et Boutelje (Ciprés de la Cordillera) to extend streamflow series of the Limay and Neuquén rivers in Argentinean Patagonia back to 1601, reporting a correlation (r) of 0.73 between instrumental and reconstructed streamflow. Tree-ring series from *A. chilensis* in Central Chile have been used to reconstruct the Atuel River streamflow in Mendoza Province, Argentina (34°S, Cobos and Boninsegna, 1983). Tree-ring records from Chile have also been successfully used to reconstruct temperatures (e.g. Villalba, 1990; Lara and Villalba, 1993; Aravena et al., 2002; Villalba et al.,

2003) and precipitation (e.g La Marche et al., 1979; Boninsegna, 1988; Lara et al., 2001) on century to millennial timescales. These high-resolution climate reconstructions for South America show low-frequency (centennial or even millennial) variability and trends (Bradley, 1991; Villalba et al., 2003) and demonstrate the potential to develop long reconstructions of streamflow in Chile.

Tree-rings and streamflow

Correlation analyses were used to examine the relationships between 30 standard tree-ring chronologies (year t and $t+1$) from Central Chile and adjacent Argentina between 39°40′ and 43°S and streamflow records for the Valdivia, Bueno and Puelo Rivers over the period from 1929 to 2002. Several species were evaluated as potential predictors namely, *Pilgerodendron uviferum* (D. Don) Florín (Ciprés de las Guaitecas), *Nothofagus pumilio* (Poepp. Et Endl.) Krasser (Lenga), *Fitzroya cupressoides* (Molina) Johnston (Alerce) and *Austrocedrus chilensis* (D. Don) Florín et Boutelje (Ciprés de la Cordillera).

Río Bueno has an average streamflow of 378 m^3/s near its mouth. It has a rainfall regime with a single winter flow peak (June–August: 557–600 m^3/s). The composite Río Bueno streamflow record was developed by averaging standardized discharge records from seven stations in the drainage basin for the period 1929–2002.

A composite tree-ring series (1223–2000) was developed by averaging two *P. uviferum* chronologies from Chile (Pozo Mallín and Río Panco, 39°40′S) with two regional composite *Austrocedrus chilensis* chronologies from five sites in Argentinean Patagonia (39°56′ and 40°44′S). The maximum correlation for Río Bueno streamflow ($r = 0.59$ $P < 0.001$, 1929–2000) was obtained using this two-species composite series as a single predictor for streamflow in the previous summer, i.e. the tree-ring formed between October 1999 and March 2000 in these chronologies is best correlated with streamflow from January to April 1999.

Tree-ring growth follows a similar pattern to streamflow variability with fluctuations around the mean in the 1929–2002 period (Fig. 1). The lowest streamflow is

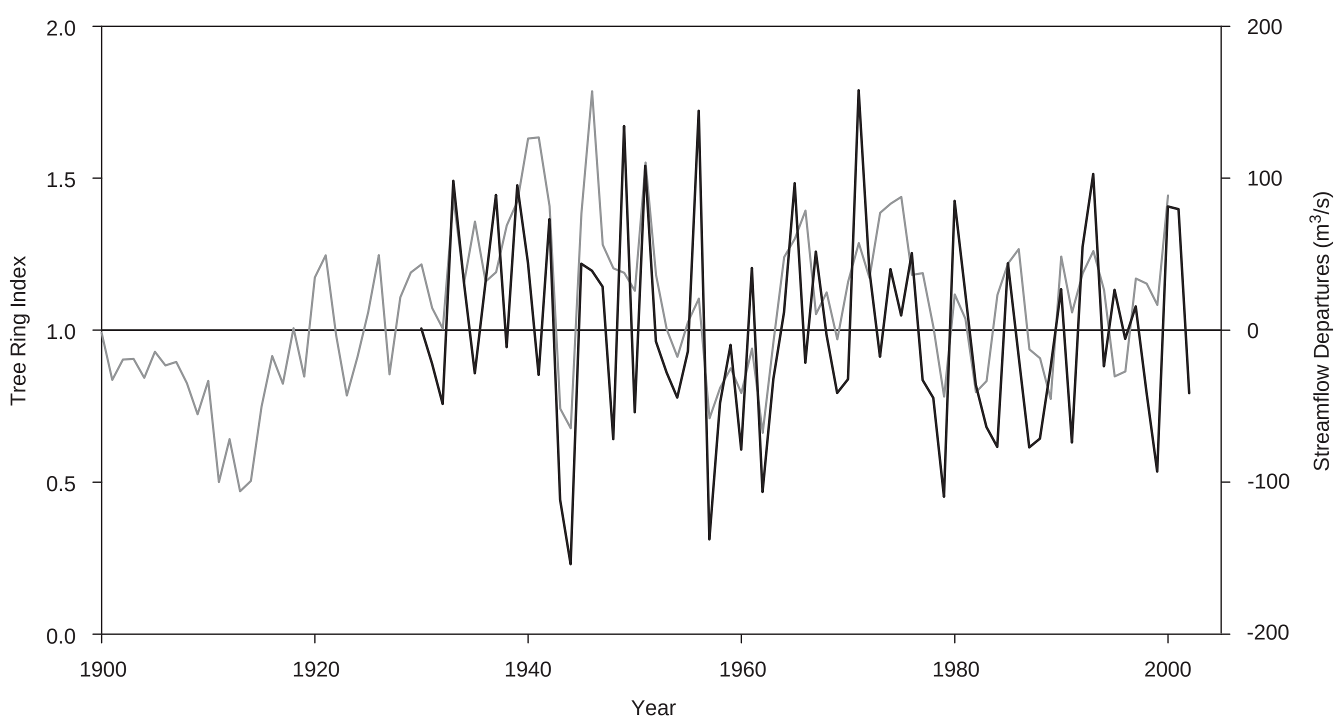

Fig. 1. Comparison of tree-ring and streamflow data for the Río Bueno watershed, 1929–2000. The tree-ring indices are an average of a composite *Pilgerodendron uviferum* chronology from two sites in Chile (Pozo Mallín and Río Panco) and two regional composite *Austrocedrus chilensis* chronologies from five sites in Argentinean Patagonia. The streamflow data are the average monthly January–April discharge for the previous summer from seven gauges in the Río Bueno watershed ($r = 0.59$, $P < 0.001$, 1929–2000). *Note*: because of the Schulman convention of dating Southern-Hemisphere tree rings to the year in which growth is initiated, these two series appear to be synchronous although the January–April streamflow is actually correlated with the growth season extending (December–April) into the subsequent calendar year.

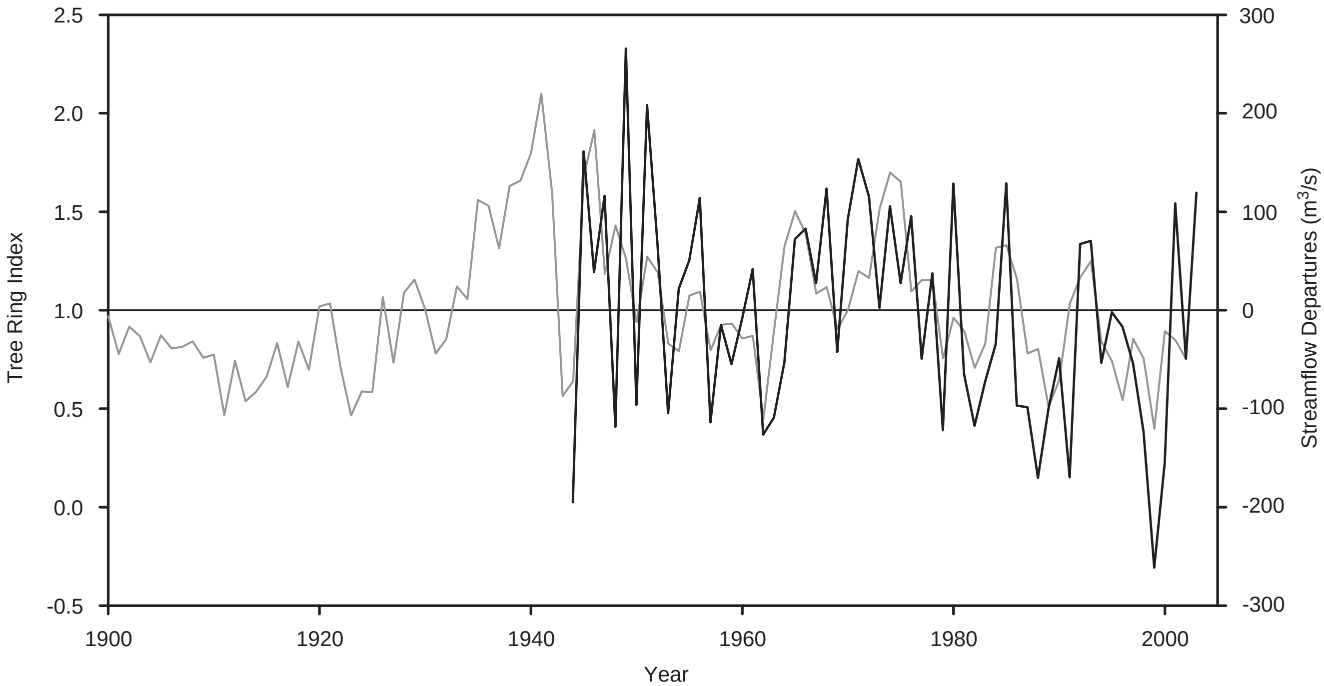

Fig. 2. Comparison of tree-ring and streamflow data for the Río Puelo watershed, 1943–2002. The tree-ring chronology is from *Austrocedrus chilensis* at the Centinela site in Argentinean Patagonia. Streamflow data are the average monthly November–April discharge for the previous growing season based on five records in the Río Puelo watershed ($r = 0.57$, $P < 0.001$, 1943–2002).

recorded for 1943, which has been identified as the driest year in Northern Argentinean Patagonia and Central Chile between 1837 and 1989 (Villalba et al., 1998; Lara et al., 2001). Other years of low streamflow are: 1956, 1961, 1978 and 1998 (Fig. 1). We also examined the correlation between tree-ring variables and streamflow for Río Puelo. This river has an average streamflow of 644 m^3/s near its mouth and a mixed rainfall–snowmelt regime: the main peak is in winter (May–July: 771–866 m^3/s) with a secondary, snowmelt peak in late spring (November–December: 712–761 m^3/s). This river has a small headwater contribution from glaciers in Argentina. The composite streamflow record for Río Puelo was developed by averaging standardized discharge records from five gauges along the river (41°40′–42°12′S). The highest correlation with tree rings ($r = 0.57$, $P < 0.001$, 1943–2002, Fig. 2) was obtained between November and April streamflow of the previous growing season and the *A. chilensis* chronology from Centinela (40°44′S) in Argentinean Patagonia. Over the instrumental record (Fig. 2), tree-ring variations track the low and high-frequency patterns in the discharge data for the period 1943–2002, with the lowest values for tree-ring width and streamflow in 1943, 1997 and 1998.

The tree-ring series that correlate with the discharge of the Río Puelo (Fig. 3) and Río Bueno (not shown) demonstrate low-frequency variability throughout their record and hence the potential to reconstruct low-frequency variability in the streamflow over the last 500–780 years. An interesting feature of this low-frequency variability is the positive trend in the tree-ring records between 1915 and 1941 whereas both the tree-ring record and Río Puelo streamflow clearly show a decreasing trend after 1941 (Figs. 2 and 3). These initial correlations are encouraging and new *P. uvíferum* and *A. chilensis* chronologies are being developed or updated to improve correlations with streamflow. When completed, this expanded chronology base should allow the development of long discharge reconstructions for Río Bueno and Río Puelo.

Tree-rings and salinity in estuaries

In the estuaries and inshore fjords of the Chilean Lake region water salinity increases in summer and early autumn due to reduced direct precipitation inputs and the low contributory streamflow from the large rivers. This salinity increase is potentially a major limitation on the production of farmed salmon in the estuaries because of the poor tolerance of juveniles (smolts) to marine conditions and the lower oxygen levels which increase mortality (León, 2005). Water salinity at a 0.5 m-depth has been sampled 1–3 times per month at

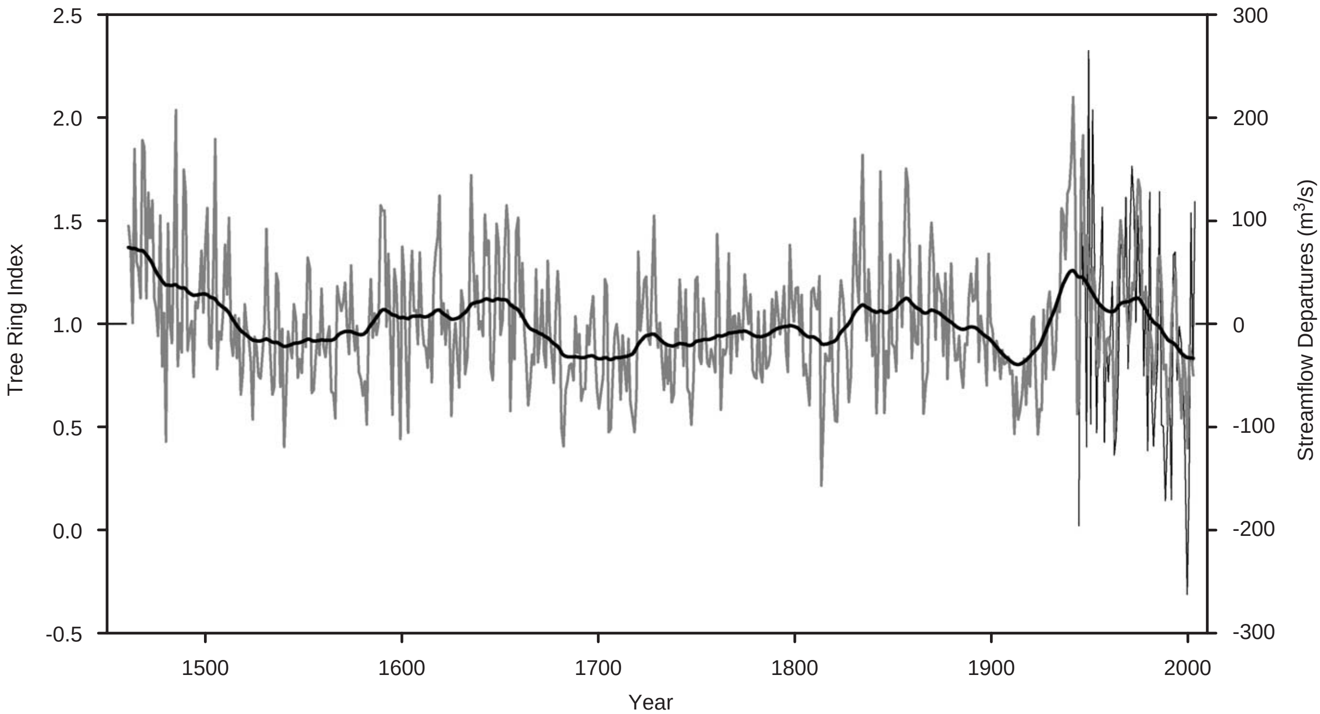

Fig. 3. Low-frequency trends in the tree-ring chronologies correlated with Río Puelo streamflow (1461–2002). The solid line is a low pass filter (Essenwanger, 1986). The instrumental discharge record is also shown for comparison (1943–2002).

Caleta Martin and Chaparano in the Reloncavi Estuary near the mouth of Río Puelo since 1992 (data provided by INTESAL, Instituto Tecnológico del Salmón, Puerto Montt). There is a negative correlation ($r = -0.72$) between March and April water salinity and the average streamflow of Río Puelo for the same period between 1992 and 2000. There is also a significant correlation ($r^2 = 0.60$, $P < 0.01$, 1992–2000) between the ring-widths of the composite standard *Pilgerodendron* chronology from the Pozo Mallín and Panco sites and the contemporaneous summer water salinity (January–April) at the Reloncaví Estuary (Fig. 4). This is consistent with the weak negative correlation ($r = -0.31$, ns) between *Pilgerodendron* tree-rings and contemporaneous January–April streamflow.

Concluding remarks

A recent review of dendrochronology in Chile identified streamflow reconstruction as a high research priority (Lara et al., in press). The development of a network of streamflow-sensitive tree-ring chronologies and its integration with instrumental hydrological data can provide an adequate understanding of the spatial and temporal patterns of streamflow and precipitation in the Valdivian Rainforest eco-region.

One of the *Pilgerodendron* streamflow-sensitive tree-ring chronologies presented here begins in 1223 AD. These preliminary results demonstrate the potential to develop long streamflow reconstructions. Long-term studies are also needed on the depletion of runoff volumes resulting from recent anthropogenic influences on streamflow regimes as a result of land-use changes (e.g. from native forests to plantations). These studies should use a combination of techniques including tree-rings, instrumental records and land-use forest cover history from aerial photographs.

If the correlation between tree-rings and water salinity of the estuaries in the period 1992–2000 can be verified using longer data sets, this would indicate the potential to reconstruct past variability in water salinity from the tree-ring data. For this purpose, it is important to maintain and develop new records that monitor water salinity and other water quality attributes. This would be relevant for the understanding of the long-term fluctuations in the carrying capacity for fish production and how it responds to climate change.

Reconstructions of streamflow, salinity and other water quality variables over the last several centuries in Southern Chile could provide critical inputs to the modeling of future scenarios of water availability that are crucial for adequate decision-making and planning of resource management in the Valdivian Rainforest eco-region. These techniques may also be applicable to

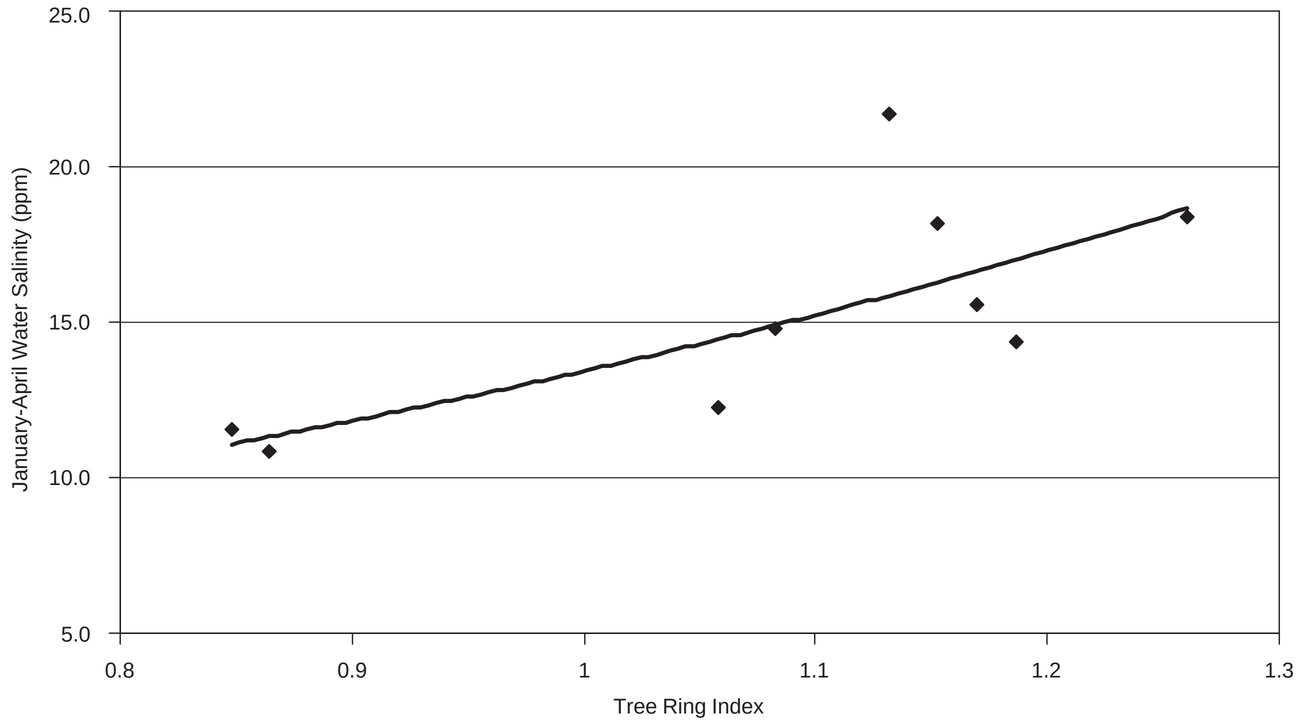

Fig. 4. Comparison of tree-ring indices and estuarine salinity 1992–2000. The tree-ring indices are a composite of chronologies from *Pilgerodendron uviferum* at Pozo Mallín and Río Panco in Chile. The salinity data are average January–April water salinity at 0.5 m-depth from two sampling points in the Reloncaví Estuary for the current summer (e.g. tree ring of 1999 with the water salinity of January–April 2000, $r^2 = 0.60$, $P < 0.01$, 1992–2000). Correlation was calculated using a power function and is plotted as a trend line.

other regions where fresh water supply is relevant for estuarine functioning.

Documenting the recent (1990–1999) contrasting streamflow and precipitation patterns between Chile and adjacent Argentina (see IPCC, 2001) and similar changes in the past may also lead to improved understanding of the effect that changes in oceanic and atmospheric circulation have on climate variability in this region.

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