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ORIGINAL PAPER

Relating land cover to stream properties in southern Chilean watersheds: trade-off between geographic scale, sample size, and explicative power

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Abstract Several studies relating land cover to stream properties have used sample sizes of more than 100 watersheds, but the variance that they explain is moderate to low (R^2 less than 50%), limiting the predictive value of these studies when their models are applied to watersheds that were not included in the models' development. We hypothesize that this is due to the increases in variation that occur with increases in sample size and in the geographic scales of the areas in which the watersheds are distributed. Land cover alone cannot explain all of that variation; more predictors must be considered. Conversely, models with high explicative power would require relatively small sample sizes distributed over small areas. This hypothesis was evaluated sampling 17 watersheds from southern Chile's Lake Region, for which we developed regressive models between land cover/watershed area/precipitation/geomorphology and stream properties (i.e., conductivity, temperature). With a maximum $n = 15$ watersheds, on a regional scale, a poorly explained variation in hydrologic variables (mean 37–49%) was obtained. The R^2 increased slightly, to 45–52%, when precipitation was included as a predictor. In half of the cases analyzed, the models improved when geomorphology was considered as an additional predictor (60–66%), supporting our hypothesis. Furthermore, when our analysis was restricted to a narrower latitudinal span ($n = 9$), the R^2 was much stronger (68–87%) when only land cover and watershed area were included as predictors. These percentages also increased when more predictors were incorporated. Nevertheless, a portion of unexplained variance remained that would require the consideration of more predictors, such as geology and edaphology. The documented trade-off provides evidence that argues against the spatial generality of land cover/stream property models.

Keywords Geomorphology · Land cover · Precipitation · Temperate forests · Water flow · Water quality

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Introduction

Many studies have shown that water quality and the amount of water drained by watersheds depend partially on the land covers that characterize the landscape. For instance, streams associated with fertilized pasturelands (which originated after native forests were cleared) contain higher levels of nitrate compared to streams within forested areas (Brady and Weil 2000; Oyarzún and Huber 2003). Conversely, some pasturelands are not fertilized, and their nitrogen exports could be lower than those of forested streams (Thomas et al. 2004). Regarding the hydrologic regime, native forest watersheds could produce more water than landscapes dominated by pine plantations (Otero et al. 1994; Putuhena and Cordery 2000). Native forests also regulate stream flows better, giving rise to streams with lower flows during winter and higher flows during summer, compared to streams originating in plantations (Otero et al. 1994; Oyarzún et al. under review). Further, plantations also produce sediment exports to the water that are between 15 and 81% greater than those from native forests (Otero et al. 1994). In addition to land cover, other factors, such as soil characteristics, slope, precipitation, and in-stream-losses of nutrients can influence concentrations of chemicals in streams (Dillon and Molot 1992; Moore et al. 2004).

Most landscapes have been modified from their original states by human interventions that have contributed to the creation of a mosaic of cover types (shrublands, pasturelands, forests, cities, etc.) (Strayer et al. 2003; Biggs et al. 2004). For this reason, predicting the effects of land cover on stream characteristics may be difficult, because an array of land covers can occur in a single watershed. Simple statistical modelling tools can enable one to study the behaviour of an ecosystem when one has numerous predictor variables (Herlihy et al. 1998; Strayer et al. 2003). The aforementioned studies have used sample sizes of more than 100 watersheds, permitting the evaluation of the mathematical relationships between predictor and criterion variables (i.e., the slopes of the regression models) with high precision. However, the percentage of variance explained by land cover is usually moderate to low ($R^2 \leq 0.55$) (Herlihy et al. 1998; Strayer et al. 2003). On the other hand, Moore et al. (2004) used a more restricted data set, from 67 watersheds, which produced a much better fit using a more complete set of predictors and non-linear models. We hypothesize that the reduced explicative power of studies that encompass more extensive areas is due to the amount of variation, which increases with larger sample sizes and with the broader geographic scales of the areas in which the watersheds are distributed. Therefore, a small set of predictors cannot produce a very good fit. The problem could be resolved by including more predictors (such as precipitation, geology, geomorphology, etc.), but the sample size must increase accordingly to keep an adequate ratio of cases to variables, in order to allow the precise estimation of parameters in multiple regression models. If these new cases (sites) are not from the same area in which the original data set was collected, it is likely that more variation will be produced, returning one to the above problem of the need for additional predictors. In other words, we foresee models that have robust explicative powers, but only when used with relatively small sample sizes distributed at local scales. Conversely, at larger regional scales, and with larger sample sizes, the models' explicative powers are expected to be low. This trade-off could provide evidence favouring the argument against the spatial generality of land cover/stream property models.

We evaluated our hypothesis using a set of watersheds from southern Chile's Lake Region. This mostly-forested landscape has a mosaic of land cover types, which provides an ideal opportunity for study of this topic, which is especially relevant considering that the Southern Hemisphere's streams are not as impacted by acid rain and other chemical contaminants as comparable Northern Hemisphere streams often are (Hedin et al. 1995; Pérez et al. 1998). Therefore, we may be able to explore the landscape's influence on stream properties without considering additional perturbations, such as nitrogen deposition.

In order to evaluate our hypothesis, we developed multiple regression models relating land cover types, watershed area, precipitation, and geomorphology to some physical and chemical hydrologic variables.

Study area

Chile contains most of South America's temperate rainforest area, which accounts for more than half of the area of temperate forest in the Southern Hemisphere (Donoso 1993). The forests of southern Chile and adjacent Argentina, located from 36° S through 48° S latitude, are defined as the Valdivian Rainforest Eco-region (Dinerstein et al. 1995). In addition to having been affected by natural disturbances, such as volcanism, tectonic events, and landslides (Veblen et al. 1995; Armesto et al. 1998), native forests in this region have been affected by human disturbances, including degradation due to poor logging practices, conversion of forested land to agricultural fields (Donoso and Lara 1995), replacement of native forests by fast-growing exotic tree plantations (Lara and Veblen 1993; Lara et al. 1995), and human-set fires (Donoso and Lara 1995). These disturbances have fragmented the natural landscapes, contributing to the creation of a land cover mosaic that has probably altered the ecosystem services that were at one time provided by the original native forests (Lara et al. 2003). Forestlands that have persisted through such disturbances now support second-growth stands of native species (Echeverría and Lara 2004) or have been transformed into shrublands composed of a combination of native and exotic species.

Methods

Watersheds

The sampled watersheds were distributed in the main physiographic zones of southern Chile's Lake Region (39.5°–41.5° S). These zones are known as the Coastal Range, the Intermediate Depression, and the Andean Range (Fig. 1). There is also another mountain range (the Loncoche Range), which connects the Coastal and Andean Ranges along the northern portion of the study area (Fig. 1). We sampled 17 watersheds within the large basins of the Valdivia, Bueno, and Maullín rivers. We selected watersheds that met the following criteria: water flows above 0 m s^{-1} throughout the year, with mean depths between 0.1 and 1.5 m, and current speeds below 2 m s^{-1} (Table 1, Fig. 1). The watersheds were relatively small, covering between 0.3 and 14.5 km^2.

Native vegetation is characterized by evergreen forests in the Coastal Range and in the foothills of the Andean Range, south of the MANZ watershed (Fig. 1, watershed 12). In this area, the main native tree species are *Aextoxicon punctatum* R. et P., *Drimys winteri* J.R. et G. Forster, *Nothofagus* spp., and *Laureliopsis philippiana* (Looser) Schodde. North of MANZ watershed, within the Andean Range, forests are mainly composed of *N. obliqua* (Mirb.) Oerst., *N. alpina* (Poepp. et Endl.) Oerst. (both deciduous trees), and *N. dombeyi* (Mirb.) Oerst. (evergreen trees). The Intermediate Depression is occupied by extensive prairies and pasturelands, which were formerly forested areas, dominated by the grasses, *Holcus lanatus* L. and *Poa annua* L. Lastly, exotic tree plantations of *Pinus radiata* D. Don and *Eucalyptus* spp. are mostly found in the Coastal Range (Donoso 1993).

Land-use and land-cover mapping

The literature suggests that land cover is relevant to water quality and flow regime (Otero et al. 1994; Hedin et al. 1995; Oyarzún and Huber 2003; Thomas et al. 2004). Land-use and land-cover mapping were performed following the methods described by Lara and Sandoval (2003), which were specifically designed for making detailed descriptions of small study areas ranging from less than one to more than 100 km^2. Aerial photographs were taken at a scale of 1:8,000–1:10,000. Using these, we preliminarily described different homogeneous cartographic units (HCUs). Thereafter, all watersheds were ground-truthed in the field to assure adequate delimitations and improved descriptions of the HCUs. Finally, we prepared maps that were integrated with a Geographic Information System using ArcView 3.2 software (Environmental Systems Research Institute, Inc., USA). The areas of each HCU and overall watershed were calculated by this software. Watershed area was considered a predictor because previous studies have shown it to be a useful, indirect expression of a number of

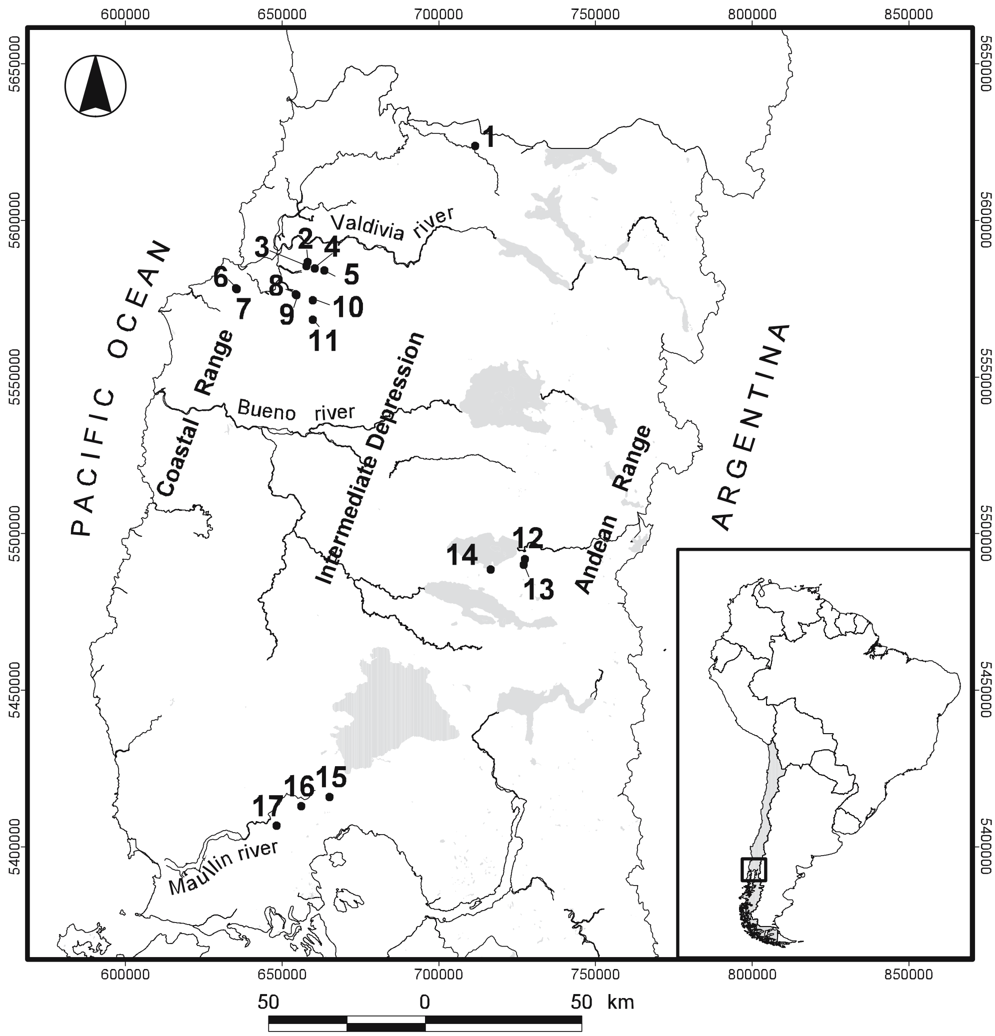

Fig. 1 Watersheds studied in Chile's Lake Region. Code: 1 = CUGA, 2 = LLAN, 3 = SEND, 4 = TORN, 5 = PILO, 6 = SJUA, 7 = MINA, 8 = JOA1, 9 = JOA2, 10 = GUIN, 11 = PLAT, 12 = MANZ, 13 = CHAN, 14 = NILQ, 15 = LAN1, 16 = QUEM, 17 = GATI. For complete names, see Table 1

variables that influence stream properties, such as human population density, travel distance of water towards the sampling point, differences in explicative powers over varying watershed areas, etc. (Strayer et al. 2003; Biggs et al. 2004).

We distinguished seven land-cover types expressed as percentages of cover (Universidad Austral de Chile et al. 1995; Lara and Sandoval 2003). We used percentages of land cover instead the actual areas, because it is more informative to know what percentage of the landscape is occupied by a given land cover. (1) Prairies, pasturelands, and agricultural lands, mostly unploughed, all originated from the clearing of native forests, and are considered prairies in the broad sense. (2) Shrublands, including both pasturelands and shrublands, which can have up to 25% cover of sparse trees or scattered forest stands. (3) Second-growth native forests, originating after anthropogenic and/or natural disturbances, are generally homogeneous in their vertical and diameter structures; this category includes purely second growth stands as well as mixed stands that include old-growth individuals. (4) Old-growth native forests are generally heterogeneous in their vertical structures, crown sizes, tree diameters, and

Table 1 Watersheds studied in Chile's Lake Region

Code	Main basin	Stream name	Latitude* UTM (m)	Longitude* UTM (m) (Huse 18)
CHAN[a,b]	Bueno	Pichichanlelfu	5490208	727308
CUGA[a,b]	Valdivia	Curirruca grande	5623864	711729
GATI[b]	Maullín	Gatito	5406779	648457
GUIN[b]	Valdivia	Guindos	5574653	659941
JOA1[a,b]	Valdivia	Joaquines 1	5576251	654737
JOA2[a,b]	Valdivia	Joaquines 2	5576586	654450
LAN1[b]	Maullín	Lahueñadi 1	5416015	665294
LLAN[a,b]	Valdivia	Llancahue	5586874	658324
MANZ[a,b]	Bueno	Manzano	5491905	727641
MINA[b]	Valdivia	Las Minas	5578386	635385
NILQ[b]	Bueno	Ñilque	5488661	716758
PILO[a,b]	Valdivia	Pillo-Pillo	5584148	663630
PLAT[a,b]	Valdivia	La Plata	5568385	659958
QUEM[b]	Maullín	Las Quemas	5413105	656236
SEND[a,b]	Valdivia	Senderos	5585617	657897
SJUA[a,b]	Valdivia	San Juan	5578149	635652
TORN[a,b]	Valdivia	Tornagaleones	5584788	660589

* These approximate the locations of the water sampling points

[a] Watersheds used for model development when sample size was 8–9

[b] Watersheds used for model development when sample size was 14–15

tree ages; this category also includes dwarf trees (krummholz), typical of timberlines, which could be between 2 and 8 m in height. (5) Plantations with adult trees (12–22 years old, >75% canopy cover) and (6) Plantations of young trees (1–5 years old, <25% canopy cover). Plantations are composed of either *Pinus radiata* or *Eucalyptus* spp. Plantations of intermediate ages (6–11 years old) were not found. (7) Other covers, including small lakes, wetlands, roads, urban sites, snowfields, and bare soil. As this combined category generally occupies a small proportion (< 5%) of the studied watersheds, and likely has a minor effect on hydrologic variables, we did not consider it in the analyses. Furthermore, we did not want to have an excessive number of independent variables, as our sample size was relatively small (9–15 watersheds).

Precipitation and water flow

Chile's Lake Region is characterized by a humid temperate climate with a moderate Mediterranean-type climatic influence (di Castri and Hajek 1976). There is year-round precipitation ranging from 1,100 to 5,000 mm (Pezoa 2003). Our data showed that most of our hydrologic variables changed only between 0 and 10% on a monthly basis, but we are aware that stream variables can change even more over the long term (Little 2005, and personal communication). Therefore, we discriminated between two sampling seasons, a rainy season (July–September) and a drier season (January–May), considering that monthly precipitation during those respective periods is usually above and below the monthly mean precipitation. Notwithstanding, we consider our samplings to be representative of the particular months in which the water samples were collected, but not necessarily of the overall season. In order to develop models for these contrasting seasons, we studied the rainy season of 2003 and the dry seasons of 2003 and 2004.

Precipitation is an important predictor because it can affect the delivery of nutrients from the land surface to streams by determining the volume and rate of runoff (Moore et al. 2004). Rainfall was recorded with rain gauge collectors connected to a HOBO Data Logger (Onset Computer Corporation, Massachusetts, USA). In addition, daily information was obtained from small pluviometers (area = 95 cm^2) installed in each watershed. Rain gauges and pluviometers were installed in open areas (no trees within 20 m of the measuring point) of eight watersheds in the neighbourhood of the water sampling points. Some watersheds were very close to each other, and we assumed that the amounts of precipitation that they received were very similar when no data were available for a particular watershed. Daily measures were taken from August 2002 to March 2004. Rainfall was analyzed as accumulated precipitation over the season (rainy or dry) and as the coefficient of variation (CV) calculated from the daily measurements. This coefficient is a measure of how variable precipitation is. The effects of extreme rainfall events on streams can be predicted from this coefficient.

Stream water discharge was estimated from daily visual observations of rods measuring water levels. This method was calibrated against direct evaluations of stream flow by the velocity-area method; thus, the cross-sectional area and the current velocity were measured several times with a Hydro-Bios Kiel Cat. 445 500–033 (Germany) current meter during the study period 2002–2004. The relationship between water level and water flow was determined using linear and quadratic equations. Stream water discharges were analyzed as mean values and as coefficients of variation calculated from the long-term data collected for each season. We also measured stream flow directly once or twice every season, visiting each site at the same date for water sample collection; those measurements were recorded as instantaneous flow.

Daily readings from pluviometers and rods were taken between 9 and 10 A.M.

Geomorphology

Geomorphology deserves attention because some of its components, such as the watersheds' slopes, can also control the delivery of nutrients to streams (Dillon and Molot 1992; Moore et al. 2004). All these variables were calculated using the Spatial Analyst extension of ArcView 3.2. We expressed geomorphology as the mean slope of each watershed, averaging each cell across the watershed. We also considered the differences between the maximum and minimum elevations of each watershed. Furthermore, the compound topographic index (*CTI*) was incorporated into models, as it has been shown to be a powerful geomorphic variable in many other studies (e.g., Quinn et al. 1995; Yang et al. 2005). This index is expressed as

$$\mathrm{CTI} = \ln(a/\tan\beta)$$

where ln is the natural logarithm, a is the upslope contributing area per contour length for each land pixel, tan is the tangent function, and β is the slope of the respective pixel. *CTI* was calculated for cells of 25 m × 25 m across the entire watershed, and then it was averaged in order to obtain a unique value for each watershed. High *CTI* values generally indicate landscapes with gentle slopes, and low *CTI* values generally indicate landscapes with steep slopes.

Water quality

A set of standard variables for water quality assessment was measured at the lower limit of each watershed once or twice every season. We purposely sampled after at least three days without heavy rains, to avoid collecting from storm flows. Selected variables (e.g., conductivity, temperature, nutrients, etc.) are relevant to water use by humans; in addition, they can influence the autochthonous productivity of the stream, thereby indirectly affecting food available to fish. By way of example, moderate concentrations of nitrate and ammonium are needed to support stream productivity and, therefore, fish populations (Stockner and Shortreed 1978; Stockner and MacIsaac 1996). In addition, high concentrations of nitrate favour excessive algal growth, causing water eutrophication (Vitousek et al. 1997). In general, water quality is important for sport fishing and salmon farming (Soto and Lara 2001).

Conductivity and pH were measured in a beaker in the field using 250-ml samples of water taken from the surfaces of pools (where speeds were below 70% of those measured in the centers of the streams). We used the following Thermo Orion sensors (United Kingdom): conductivity, DuraProbe Epoxy graphite cells (range 0–1999 μS cm^{-1}); for pH, Aqua Pro pH flat surface. For temperature measurements, we inserted a multiparameter Thermo Orion Model 1230 probe into the centers of the streams, waiting for the readings to stabilize before recording them.

Water nutrient samples were collected in 1 l plastic bottles that had been previously washed with 1% chlorhydric acid. The bottles were first rinsed with 100 ml of water taken from a central point on the streams' surfaces. The bottles were capped and shaken, and the water was discarded. Thereafter, 950 ml samples were taken, the capped bottles were kept at cool temperatures (below 5°C) and the samples were frozen within 6 h of being collected. Samples were analyzed within 1–2 weeks of being collected. Nitrate was measured by the cadmium reduction method, ammonium was measured by the phenol salt method, orthophosphate was measured by the heptamolybdate method, total phosphorus was measured, after oxidation and autoclaving, by the heptamolybdate method, and dissolved organic nitrogen (DON) was measured, using filtered water, by the Kjeldahl method, discounting ammonium concentration. The lower detection limit was $<1\ \mu g\ l^{-1}$. Methodologies for these analyses can be found in Wetzel and Likens (1979) and Zahradnik (1981).

Data analysis

Water quality and flow regime variables were analyzed separately as dependent variables. For predictors, we used six land cover types (prairies, shrublands, old-growth and second-growth native forests, and adult and juvenile plantations), watershed area, seasonal precipitation, the coefficient of variation of daily precipitation throughout the respective season, the mean slope of each watershed, the difference between the maximum and minimum altitudes for each watershed, and the compound topographic index.

We included the predictors in the following order: first, land cover and watershed area only; then we added precipitation, and, finally, we added geomorphology. This was done in order to evaluate whether improvements in explicative power could be made by including more and more predictors, especially for those watersheds distributed at a regional scale (see below).

In order to avoid the problem of colinearity between predictors, we had to use orthogonal predictors: we calculated Pearson correlation coefficients (r) to select only variables with non-significant associations among them. Moreover, we developed several models for the same dependent variables using different sets of predictors, none of which were correlated with other predictors within the same equation.

We used a forward stepwise multiple regression analysis to determine the most explicative model for water quality and flow regime, using the Statistica 6.0 software (StatSoft, Inc., Tulsa, Oklahoma, USA; Module Statistics, Multiple Regression: the F-to-enter was set at 0.0001 and the F-to-remove at 0). With such a low F-to-enter, we were assured that all predictor variables could potentially enter the model, but we finished the addition of variables manually when the next step produced an increase of less than 0.05 (5%) in $R^2_{(adj.)}$ (the adjusted coefficient of multiple determination), and the model was statistically significant at $P \leq 0.05$. This modality produced results identical to those that would have been obtained by following the backward stepwise protocol. We disregarded other more restrictive procedures, such as those fixing the P-to-enter and the P-to-remove at 0.05 and 0.10, respectively (Sokal and Rohlf 1995), because they produced fixed solutions that impeded to stop the addition of variables when the maximum $R^2_{(adj.)}$ was obtained. Instead, we used a combination of manual and computer procedures to avoid the inclusion of an excessive number of independent variables. This was due to our unavoidably small sample size; in Chile the Water Agency (Dirección General de Aguas, DGA) only collects data for major rivers (Peña 1999), and therefore our study of small watersheds required the special collection of data in streams not monitored by DGA. However, this sample size is representative for Chile's Lake Region; other areas of the world, like the United States, require much larger data sets (Herlihy et al. 1998; Moore et al. 2004).

As our sample units (i.e., the watersheds) were about the same in all analyses, we used the sequential Bonferroni test based on the Dunn-Šidák method for correcting the type I error α values (Sokal and Rohlf 1995).

We constructed linear models. Although natural phenomena do not necessarily have linear relationships, these models are the simplest ones, and they provide a starting point that can be made more complex with other mathematical relationships if the linear equations fit the observed data poorly. All equations were checked for normal distributions of raw residuals. When this assumption was not met, we logarithmically transformed the dependent variables.

We began our study with data for 11 watersheds from the 2003 dry season. The watersheds were located in two large basins in the Lake Region, the Valdivia River basin (the acronyms for each watershed in this basin are as follows: CUGA, JOA1, JOA2, LLAN, PILO, PLAT, SEND, SJUA, and TORN) and the Bueno River basin (containing the CHAN and MANZ watersheds) (Fig. 1). Thereafter, we increased the number of watersheds to 17. The new watersheds were from the southern portion of the study area, including the Maullín River basin (watersheds: GATI, LAN1, and QUEM), another site from the Bueno River basin (NILQ), and two other sites from the Valdivia River basin (GUIN and MINA). Although this progressive increase in sample size was unintentional, it later enabled us to develop models with different numbers of watersheds and with geographic areas of different extents. Therefore, we carried out two analyses: one with a maximum sample size of nine watersheds, and another with a maximum sample size of 15 watersheds. The exact number of sites depends on the particular variable under analysis, because not all variables were measured for all available watersheds. The addition of six watersheds appears to be a modest increase in absolute terms, but, proportionally, it represents a general increase of 67% (up to 75% in the case of nitrate concentration; compare Table 5 with Table 2). Furthermore, the point of our study lies in the effect of including new watersheds, located in different areas than the original ones, rather than the effect of increasing the number of sites.

Results

In Appendix 1 we show the ranges of the variables studied, as well as their mean values.

Regional models

At first, we used only land cover and watershed area as predictors (Table 2). The sample size was set at 15 watersheds distributed over a regional scale (Fig. 1), in order to allow comparisons with the same site numbers and identities presented in Table 3. In few cases, logarithmic transformation of the variables did not normalize the residuals. Generally, the explained variation ($R^2_{(adj.)}$) was poor, and in spite of the apparent statistical

Table 2 Regression analysis of water variables against land cover and watershed area only, for watersheds distributed on a regional scale

Variable	Rainy season 2003						Dry season 2004					
	$R^2_{(adj.)}$	F^a	df	P	n	Res	$R^2_{(adj.)}$	F	df	P	n	Res
Log_{10} (conductivity)	0.230	3.1	2,12	0.082	15	×	0.594	6.1	4,10	0.009	15	✓
Temperature	0.571	7.2	3,11	0.006	15	✓	0.376	5.2	2,12	0.023	15	✓
Log_{10} [NO_3^-]	0.149	3.3	1,12	0.096	14	✓	0.578	5.4	4,9	0.017	14	✓
Log_{10} [NH_4^+]	0.259	5.9	1,13	0.030	15	✓	0.260	5.9	1,13	0.030	15	×
Log_{10} [DON]							0.042	1.6	1,13	0.226	15	✓
Log_{10} [PO_4^{3-}]	0.293	3.9	2,12	0.050	15	✓	0.541	5.1	4,10	0.017	15	✓
Log_{10} [total P]	0.231	5.2	1,13	0.040	15	×	0.407	4.2	3,11	0.033	15	✓
Instantaneous water flow	0.734	6.5	7,7	0.012	15	✓	0.778	17.4	3,11	0.000*	15	✓
Mean water flow	0.693	15.7	2,11	0.001*	14	✓	0.749	14.0	3,10	0.001*	14	✓
Coefficient of variation of water flow	0.141	3.1	1,12	0.102	14	✓	0.597	7.4	3,10	0.007	14	✓
Mean $R^2_{(adj.)}$	0.367						0.492					

Asterisks indicate statistically significant models according to the sequential Bonferroni test. Some variables (pH, and DON for the rainy season of 2003) are missing because the sample sizes for these variables were below seven

[a] Abbreviations: F = Fisher value; df = degrees of freedom; P = probability; n = sample size; Res = normal distribution of residuals; DON = dissolved organic nitrogen

significance of several models, only water flow was truly statistically significant after the Bonferroni's correction (asterisks in Table 2). The mean $R^2_{(adj.)}$ was 0.367 and 0.492 for the rainy and dry seasons, respectively.

Therefore, we decided to include precipitation as a predictor. Again, only about half of the models explained more than 50% of the variation (Table 3). Most models were statistically significant at $P \leq 0.05$, but temperature and water flow produced more statistically significant models (according to Bonferroni's test). The mean values for the rainy and dry seasons $R^2_{(adj.)}$ were 0.454 and 0.522, respectively. Although some particular equations improved their explained variation (e.g., conductivity and total phosphorus; compare Tables 2 and 3), the overall result is only a slight improvement (3–9%) compared to the models that only considered land cover and area, and we conclude that the explicative power of many regional models continues to be poor.

In order to evaluate the possible contributions of different geomorphologies to the unexplained variations at the regional scale, we included the mean slope, the difference between the maximum and minimum altitudes of each watershed, and the compound topographic index as predictors. We found that in about 50% of the cases analyzed, the $R^2_{(adj.)}$ increased, in some cases noticeably (e.g., nitrate and DON, Table 4). Some models turned out to be statistically significant in comparison with those of Table 3 (e.g., nitrate and coefficient of variation of water flow). The mean $R^2_{(adj.)}$ also improved (60–66%) (Figure 2).

Local models

We analyzed data from a more restricted latitudinal range, using only land cover and watershed area as predictors (Table 5). This analysis was conducted because we obtained good $R^2_{(adj.)}$ values for the dry season of 2003 using these predictors (n = 9 watersheds, located in the contiguous Valdivia and Bueno river basins, Fig. 1). These data are not shown, as we only had data for nine watersheds and we could not verify whether the results were similar with a more comprehensive set of 15 watersheds. Instead, comparisons were possible with the other seasons (rainy 2003 and dry 2004). It is striking that the explained variation increased in most cases when comparing Table 5 with Table 2: several $R^2_{(adj.)}$ values were very high (> 0.9) during the dry season (e.g., conductivity and nitrate, Table 5). During the rainy season, the explained variation was generally lower than it was during the dry season (e.g., orthophosphate and water flows). This is shown by comparing mean $R^2_{(adj.)}$ values of both seasons, being 0.681 for the rainy season versus 0.870 for the dry season. Both values can be

Table 3 Regression analysis of water variables against land cover, precipitation, and watershed area, for watersheds distributed on a regional scale

Variable	Rainy season 2003						Dry season 2004					
	$R^2_{(adj.)}$	F^a	df	P	n	Res	$R^2_{(adj.)}$	F	df	P	n	Res
Log_{10} (conductivity)	0.500	8.0	2,12	0.006	15	✓	0.683	11.0	3,11	0.001	15	✓
Temperature	0.707	12.3	3,11	0.001*	15	✓	0.515	4.7	4,10	0.021	15	✓
Log_{10} [NO_3^-]	0.149	3.3	1,12	0.096	14	✓	0.578	5.4	4,9	0.017	14	✓
Log_{10} [NH_4^+]	0.259	5.9	1,13	0.030	15	✓	0.260	5.9	1,13	0.030	15	×
Log_{10} [DON]							0.042	1.6	1,13	0.226	15	✓
Log_{10} [PO_4^{3-}]	0.421	6.1	2,12	0.015	15	✓	0.541	5.1	4,10	0.017	15	✓
Log_{10} [total P]	0.479	7.4	2,12	0.008	15	✓	0.427	4.5	3,11	0.028	15	✓
Instantaneous water flow	0.734	6.5	7,7	0.012	15	✓	0.778	17.4	3,11	0.000*	15	✓
Mean water flow	0.693	15.7	2,11	0.001*	14	✓	0.749	14.0	3,10	0.001*	14	✓
Coefficient of variation of water flow	0.141	3.1	1,12	0.102	14	✓	0.648	9.0	3,10	0.003	14	✓
Mean $R^2_{(adj.)}$	0.454						0.522					

Asterisks indicate statistically significant models according to the sequential Bonferroni test. Some variables (pH, and DON for the rainy season of 2003) are missing because the sample sizes for these variables were below seven

[a]Abbreviations: F = Fisher value; df = degrees of freedom; P = probability; n = sample size; Res = normal distribution of residuals; DON = dissolved organic nitrogen

Table 4 Improvement of models when incorporating geomorphology as a predictor. This was expressed as the mean slope, the difference between the maximum and minimum altitudes of each watershed, and the mean compound topographic index

Variable	Rainy season 2003						Dry season 2004					
	R^2 (adj.) without geomorphology	R^2 (adj.) with geomorphology	F[a]	df	P[b]	n	R^2 (adj.) without geomorphology	R^2 (adj.) with geomorphology	F	df	P	n
Log_{10} (conductivity)	0.500	0.653	9.8	3,11	0.002	15						
Log_{10} [NO_3^-]	0.149	0.635	5.5	5,8	0.017	14						
Log_{10} [NH_4^+]	0.259	0.916	39.1	4,10	0.000*	15						
Log_{10} [DON]							0.042	0.717	12.8	3,11	0.001*	15
Log_{10} [PO_4^{3-}]	0.421	0.584	10.8	2,12	0.002	15						
Log_{10} [total P]	0.479	0.697	17.1	2,12	0.000*	15	0.427	0.452	6.8	2,12	0.011	15
Instantaneous water flow							0.778	0.901	65.0	2,12	0.000*	15
Coefficient of variation of water flow	0.141	0.334	4.3	2,11	0.043	14						
Mean $R^2_{(adj.)}$[c]		0.661						0.604				

Empty spaces or missing variables (i.e., temperature) occur when no improvement of models was achieved by incorporating geomorphology

[a]Abbreviations: F = Fisher value; df = degrees of freedom; P = probability; n = sample size; DON = dissolved organic nitrogen

[b]Asterisks indicate statistically significant models according to the sequential Bonferroni test

[c] The values for models that did not improve with the inclusion of geomorphology were also considered within this mean

All residuals were normally distributed

Table 5 Regression of water variables against land cover and watershed area, for watersheds distributed in neighbouring large basins (Valdivia and Río Bueno)

Variable	Rainy season 2003					Dry season 2004				
	R^2 (adj.)	F^a	df	P	n	R^2 (adj.)	F	df	P	n
Log_{10} (conductivity)	0.397	3.6	2,6	0.092	9	0.921	47.5	2,6	0.000*	9
Temperature	0.797	8.8	4,4	0.029	9	0.762	9.5	3,5	0.016	9
Log_{10} [NO_3^-]	0.939	22.7	5,2	0.043	8	0.961	35.6	5,2	0.028	8
Log_{10} [NH_4^+]	0.807	9.4	4,4	0.026	9	0.646	5.9	3,5	0.043	9
Log_{10} [DON]						0.845	9.7	5,3	0.045	9
Log_{10} [PO_4^{3-}]	0.401	1.9	6,2	0.386	9	0.984	84.1	6,2	0.012	9
Log_{10} [total P]	0.519	3.9	3,5	0.089	9	0.984	84.9	6,2	0.012	9
Instantaneous water flow	0.701	19.8	1,7	0.003	9	0.903	38.0	2,6	0.000*	9
Mean water flow	0.633	7.9	2,6	0.021	9	0.940	22.0	6,2	0.044	9
Coefficient of variation of water flow	0.935	29.6	4,4	0.003	9	0.757	9.3	3,5	0.017	9
Mean $R^2_{(adj.)}$	0.681					0.870				

Asterisks indicate statistically significant models according to the sequential Bonferroni test. Some variables (pH, and DON for the rainy season of 2003) are missing because the sample sizes for these variables were below seven

[a] Abbreviations: F = Fisher value; df = degrees of freedom; P = probability; n = sample size; DON = dissolved organic nitrogen

All residuals were normally distributed

considered to be relatively good, considering the limited set of predictors. Again, most models appeared to be statistically significant, although the Bonferroni's test determined that only two models (conductivity and instantaneous water flow, Table 5) were truly significant. In sum, with a sample size of nine watersheds in neighbouring basins, we can adequately explain the water variables from our predictors (land cover and area), without including precipitation and geomorphology, as we did in the regional analysis. If we include precipitation, the mean $R^2_{(adj.)}$ increases to 0.713 and 0.888 for rainy and dry seasons, respectively (Fig. 2). Finally, the inclusion of geomorphology also helps to improve the models (0.855 and 0.938, respectively).

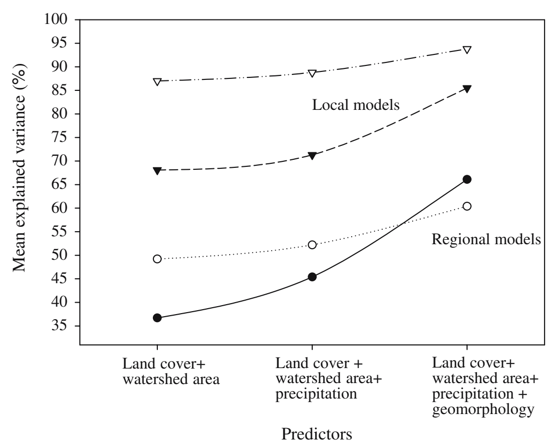

Fig. 2 Increase in explicative power of stream variables when additional predictors are incorporated. Black symbols: rainy season; white symbols: dry season

Potential confounding factors

The increase in explicative power shown in Fig. 2 could be caused by an increase in the number of predictors needed to develop the respective models (Table 6). This increase is unavoidable because, in the stepwise regression, we aimed to find the $R^2_{(adj.)}$ near the asymptote in a plot of explained variance versus the number of predictors, thereby obtaining models with an acceptable $R^2_{(adj.)}$, but without including an excessive number of predictors. Thus, we did not control for the number of variables entered in the final model. Even bearing this in mind, the percentage of explained variation per predictor increased when going from regional models, that only considered land cover and area, to those that also included precipitation and geomorphology (Table 6). The same trends were found with the models developed at local scales (n = 9), which generally had the highest explained variation per predictor. Although this variation, on a per predictor basis, is narrow, it suggests that not all the increase in

Table 6 Variation in the number of predictors as a function of the type of predictors considered for the evaluation of relationships with hydrologic variables in southern Chilean watersheds

Predictors	Rainy season		Dry season	
	Mean number of predictors	Explained variation per predictor (%)	Mean number of predictors	Explained variation per predictor (%)
Regional models				
Land cover + watershed area	2.2	18.7	2.8	17.6
Land cover + watershed area + precipitation	2.3	21.5	2.9	18.1
Land cover + watershed area + precipitation + geomorphology	3.3	23.0	2.9	22.7
Local models				
Land cover + watershed area	3.4	25.3	4.1	24.8
Land cover + watershed area + precipitation	3.2	26.5	4.7	19.5
Land cover + watershed area + precipitation + geomorphology	4.7	20.6	5.0	19.4

explicative power is due to the higher number of predictors in the more complete models.

Discussion

On the model structure

We determined that hydrologic variables can be explained by land cover, watershed area, precipitation, and geomorphology. The variation in some variables was better explained when precipitation was considered, but the mean increase in $R^2_{(adj.)}$ in these cases was slight when compared with analyses made using land cover and area as the only predictors. Although some studies do use precipitation as a predictor (Graham 1999; Moore et al. 2004), other similar studies only use land cover as a predictor (Herlihy et al. 1998; Strayer et al. 2003).

Most dependent variables (except daily water flow) were only measured once every season. Many predictors, such as land cover, watershed area, and geomorphology, are generally fixed values that do not vary with the season; it is perfectly logical to associate these predictors with fixed dependent variables. However, the other predictor, precipitation, varies with the season and was calculated from a dynamic variable that changes on a daily basis. Using this synoptic expression of precipitation, we still developed models with a good percentage of explained variation (n = 9, Figure 2). As we also collected daily precipitation data, it would be possible to make further refinements of the models that consider the amount of rainfall some days before the collection of water samples. This would produce more realistic models, but we probably would not gain enough explicative power to justify the task, except in those cases with low $R^2_{(adj.)}$ values (Tables 3, 5).

Thus, although instantaneous measures of water quality and quantity are not necessarily good descriptors of stream properties throughout the season, they correspond fairly well to static (e.g., land cover, total area, and geomorphology) and dynamic (e.g., rainfall) properties of the watersheds, as Herlihy et al. (1998) have also found for their static measures.

Trade-off between watershed homogeneity and sample size

When we considered only a maximum of nine watersheds, the percentage of explained variation was quite high, even though the watersheds were relatively small; Strayer et al. (2003) have demonstrated that high explained variation is not expected for small watersheds (1–10 km^2). Moreover, we could have expected a low probability of detecting statistically significant models, because of our small sample size compared to other studies (Herlihy et al. 1998; Caraco et al. 2003; Strayer et al. 2003), as levels of significance and $R^2_{(adj.)}$ depend on the sample size (Sokal and Rohlf 1995). Apart from the Bonferroni's correction, we had statistically significant results, probably due to the relative homogeneity in those predictor variables that were not considered in our models for the watersheds distributed across the contiguous Valdivia and Bueno river basins of the Lake Region. In other words, the differences in water variables would mainly be the consequences of varying land covers and watershed areas, the exact variables that we are considering at local scales. On the contrary, when we expanded our study to include the Maullín River basin, including some watersheds from the aforementioned basins, the $R^2_{(adj.)}$ decreased noticeably (Tables 2 and 3). This decrease probably due to subjacent variables, including geomorphology, geology, and edaphology (see below), that contribute to the differences in the hydrologic variables.

According to Strayer et al. (2003), in a similar study of 110 watersheds in the United States, increasing the number of watersheds and, in turn, increasing the geographic range, lowers the $R^2_{(adj.)}$ (maximum 0.55) because there are further variations in plant species composition, climate, and soils. As they did not include precipitation as a predictor in their models, this would probably have improved their results. On the other hand, Herlihy et al. (1998) included 368 watersheds in their study, obtaining a modest maximum $R^2_{(adj.)}$ (0.48), and discovered that they could drastically improve it by restricting their analyses to an ecoregional level (maximum 0.89) or to the main drainage basins (maximum 0.92). To obtain an explained variance of more than 80%, the sample size usually had to be reduced to less than 20 watersheds (Herlihy et al. 1998). Thus, the issue of geographic scale is intensified as the sample size increases. This is in contrast with laboratory studies, which produce better adjustments when the sample size increases.

Geomorphology

Typical watersheds with good adjustment in our models are SJUA, JOA1, JOA2, and PLAT, in the Coastal Range, CUGA, PILO, LLAN, SEND, and TORN, in the Loncoche Range, and MANZ and CHAN, in the Andean Range (Fig. 1, Table 1). These watersheds have mountainous geomorphologies, which contrasts with those of some flat watersheds, which did not produce good adjustments in our models: NILQ, which is located in the transition zone between the Intermediate Depression and the Andean Range, and GATI, LAN1, and QUEM, which are entirely within the Intermediate Depression. Only GUIN and MINA are mountainous (they are discussed below in more depth). All of the flat watersheds have mean slopes of less than 5°. For instance, those of the Maullín River basin are characterized by rivers with multiple meanders, a pattern that is typical of flat landscapes. In Table 4, we demonstrated that the explained variation could be improved by including geomorphology as a predictor. Dillon and Molot (1992) and Creed and Band (1998) have also reported that watershed slope and other topographic characteristics were correlated with nitrate exports in Canada. Even so, some unexplained variation still remains in our study, which may be the consequence of other factors, including geology or edaphology.

Geology and soils

Other studies (Johnson et al. 1997; Allan and Johnson 1997) have demonstrated that, among other variables, geology is an effective predictor of some chemical characteristics of water (e.g., nitrogen, alkalinity, and total dissolved solids) in Michigan, USA. We do not have quantitative data for all aspects of geology and soils (e.g., cover of particular rocks, concentration of various soil nutrients, soil density, pH, etc.). In these cases, it is common practice to conduct the analysis in blocks of restricted areal extension (Herlihy et al. 1998; Strayer et al. 2003), as we did with the Valdivia and Bueno river basins, in order to decrease the amount of variation expected for broad geographic scales (Table 5). Therefore, we can ask whether geology and soils really vary at a regional scale, and inversely, whether they are roughly constant at smaller local scales. We can mention the following background, which would explain a portion of the variation in water variables that our predictors do not account for on a regional scale. Both the Coastal and the Loncoche Ranges are composed of metamorphic rocks, consisting mainly of mica schist with quartz lenses (SERNAGEOMIN 1998). In some places, these rocks are overlaid by Tertiary marine sediments (Martínez and Pino 1979; Le Roux and Elgueta 2000). Although GUIN and MINA (two anomalous watersheds) are apparently located over the dominating Palaeozoic metamorphic rocks, closer inspection reveals that they are actually situated in Tertiary marine basins (i.e., they have a different basement than do the well-adjusted watersheds located in these ranges).

On the other hand, NILQ is located within a zone with deposits mainly produced by volcanoclastic fluxes from the last interglacial period (about 100,000 years ago). MANZ and CHAN, which yield good adjustments in our models, are characterized by the typical Andean volcanic and plutonic outcrops (SERNAGEOMIN 1998). South of UTM 5,450,000 m (Fig. 1), the interglacial deposits are replaced by till and outwash, belonging principally to the last glaciation (20,000 years ago, Heusser 1974). Over the outwash plains, Holocene volcanic ash was deposited, and edaphic processes transformed it, producing colloidal iron deposits. These kinds of soils, with extremely low permeability, formed bogs and ''ñadis'', which are denominations for both soils and their associated vegetation. Such is the situation with LAN1, GATI, and QUEM.

Regarding edaphology of the other watersheds, those of the neighbouring Loncoche and Coastal Ranges have volcanic soils dating to 125,000 years ago. NILQ and CUGA are characterized by modern volcanic ashes, while MANZ and CHAN possess stratified ashes (Mella and Kühne 1985).

In summary, in several cases considered here, well-adjusted and poorly-adjusted watersheds are fundamentally different in geomorphology, geology, and soils. In other cases, the two kinds of watersheds have many characteristics in common. Not necessarily all of the factors invoked, or any in particular, are responsible for the loss of adjustment in *all* anomalous watersheds. In some cases, one might be more important than another, or combinations of several causes might produce the loss of explicative power in our models.

Other idiosyncrasies

GUIN had the lowest possible transparency value. These turbid waters may result from the lowest portion of the watershed (next to the sampling point), as this area has been almost completely denuded. Since the beginning of 2002, GUIN has been planted with eucalyptus. This has caused an inconsistency with the predictions of clearer waters from the prevalent land cover in that watershed (mainly native forests) (Otero et al. 1994; Iroumé 2003). This may be a source of noise in some of our models.

Finally, Strayer et al. (2003) point out other factors that hamper the achievement of completely explained models, including: measurement error in some variables, differences in species composition within the same land cover category that has been assumed to be homogeneous, and the assumption that land cover instantaneously affects the stream variables (i.e., a time lag may exist between dependent and independent variables).

Conclusions

We conclude that hydrologic variables can be adequately explained within restricted geographic scales (i.e., a high R^2 can be obtained), based on land cover and watershed area, only when the watersheds are relatively similar to one another in those factors not included in the models (e.g., geology, relief, and soils). If the landscape encompassed by the watersheds is heterogeneous, the explained variation is expected to be lower. We have demonstrated that models of landscapes on a larger geographic scale could be improved if there are sufficient data to add new predictors, such as geomorphology. However, it may be impractical or costly to measure many variables if we consider that we must simultaneously increase the number of watersheds to create robust models, especially when the sample size is relatively small (Herlihy et al. 1998). Adding more watersheds may further increase the variation that must be explained, making it necessary to incorporate more and more predictors. Therefore, the trade-off between sample size and watershed homogeneity can result in a never-ending positive feedback loop. Alternatively, we could increase the sample size at a local scale, but this will result in a loss of spatial generality.

In summary, the distribution of sampling points at different geographic scales is likely to result in the aforementioned phenomena, regardless of what variables are measured.

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Appendix 1 Ranges of the variables measured or estimated from the 17 watersheds studied

Variable	Rainy season 2003			Dry season 2004		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Water quality variables						
Conductivity (μS cm^{-1})	31.2	17.0	91.0	59.3	19	181
Temperature (°C)	7.8	4.3	10.1	15.1	11.3	19.1
pH	8.0	6.7	9.3	8.1	7.7	8.5
[NO_3^-] (μg l^{-1})	54.0	3.3	157.8	59.0	2.9	386.0
[NH_4^+] (μg l^{-1})	7.2	1.0	39.6	69.5	1.2	966.0
[Dissolved organic nitrogen] (DON) (μg l^{-1})	70.2	7.5	141.5	66.5	25.8	230.6
[PO_4^{3-}] (μg l^{-1})	10.3	1.3	67.6	32.5	2.9	153.4
[Total phosphorus] (μg l^{-1})	16.9	5.1	94.5	45.7	5.9	221.1
Water flows						
Instantaneous flow (m^3 s^{-1})	0.956	0.015	5.832	0.119	0.012	0.288
Mean water flow (m^3 s^{-1})	0.806	0.072	2.097	0.272	0.010	1.049
Coefficient of variation of water flow (%)	48.5	8.0	96.0	60.7	5.9	153.7
Precipitation						
Seasonal rainfall (mm)	776.2	316	1967	159.6	46	325
Coefficient of variation of rainfall (%)	165.4	115.0	204.3	312.1	212.1	360.8
Land covers (both seasons)						
Old-growth native forest (%)	21.0	0.0	85.8			
Second-growth forest (%)	36.1	4.8	84.0			
Prairies (%)	9.9	0.0	47.5			
Shrublands (%)	9.8	1.4	40.9			
Adult tree plantations (%)	18.1	0.0	70.4			
Juvenile tree plantations (%)	3.9	0.0	19.3			
Watershed area (km^2)	5.5	0.3	14.5			
Geomorphology (both seasons)						
Watershed mean slope (°)	9.7	0	17.3			
Difference between maximum and minimum altude (m)	387	0	951			
Compound topographic index (adimensional)	11.1	9.7	14.8			

References

Allan JD, Johnson LB (1997) Catchment-scale analysis of aquatic ecosystems. Freshwater Biol 37:107–111

Armesto JJ, Rozzi R, Smith-Ramírez C, Arroyo MTK (1998) Conservation targets in South American temperate forests. Science 282:1271–1272

Biggs TW, Dunne T, Martinelli LA (2004) Natural controls and human impacts on stream nutrient concentrations in a deforested region of the Brazilian Amazon basin. Biogeochemistry 68:227–257

Brady N, Weil R (2000) Elements of the nature and properties of soil. Prentice Hall, New Jersey, USA

Caraco NF, Cole JJ, Likens GE, Lovett GM, Weathers KC (2003) Variation in NO_3 export from flowing waters of vastly different sizes: does one model fit all? Ecosystems 6:344–352

Creed IF, Band LE (1998) Export of nitrogen from catchments within a temperate forest: evidence for a unifying mechanism regulated by a variable source area dynamics. Water Resour Res 34:3105–3120

di Castri F, Hajek ER (1976) Bioclimatología de Chile. Vicerrectoría Académica de la Universidad Católica de Chile, Santiago, Chile

Dillon PJ, Molot LA (1992) The role of ammonium and nitrate retention in the acidification of lakes and forested catchments. Biogeochemistry 11:23–43

Dinerstein E, Olson D, Graham D, Webster A, Primm S, Bookbinder M, Ledec G (1995) A conservation assessment of the terrestrial ecoregions of Latin America and the Caribbean. WWF –World Bank, Washington, USA

Donoso C (1993) Bosques templados de Chile y Argentina. Variación, Estructura y Dinámica. Ecología Forestal. Editorial Universitaria, Santiago, Chile

Donoso C, Lara A (1995) Utilización de los bosques nativos en Chile: pasado, presente y futuro. In: Armesto JJ, Villagrán C, Arroyo MK (eds) Ecología de los bosques nativos de Chile. Editorial Universitaria, Santiago, Chile, pp 363–387

Echeverría C, Lara A (2004) Growth patterns of secondary *Nothofagus obliqua- N. alpina* forests in southern Chile. Forest Ecol Manage 195:29–43

Graham LP (1999) Modeling runoff to the Baltic Sea. Ambio 28:328–334

Hedin LO, Armesto JJ, Johnson AH (1995) Patterns of nutrient loss from unpolluted old-growth temperate forests: evaluation of biogeochemical theory. Ecology 76:493–509

Herlihy AT, Stoddard JL, Johnson CB (1998) The relationships between stream chemistry and watershed land cover data in the mid-Atlantic region, U.S. Water Air Soil Pollut 105:377–386

Heusser C (1974) Vegetation and climate of the southern Chilean Lake District during and since the last interglaciation. Quaternary Res 4:290–315

Iroumé A (2003) Transporte de sedimentos en una cuenca de montaña en la Cordillera de los Andes de la Novena Región de Chile. Bosque 24:125–135

Johnson LB, Richards C, Host GE, Arthur JW (1997) Landscape influences on water chemistry in midwestern stream ecosystems. Freshwater Biol 37:193–208

Lara A, Veblen TT (1993) Forest plantations in Chile: a successful model? In: Marther A (ed) Afforestation policies, planning and progress. Behalven Press, London, UK, pp 118–139

Lara A, Sandoval V (2003) Generación de cartografía y evaluación de recursos vegetacionales. In: Oltremari J, Thelen KD (eds) Planificación de áreas silvestres protegidas. Un manual para la planificación de áreas protegidas en Chile con especial referencia a áreas protegidas privadas. CONAMA & FAO, Santiago, Chile, pp 48–63

Lara A, Donoso C, Aravena JC (1995) La conservación del bosque nativo en Chile: problemas y desafíos. In: Armesto JJ, Villagrán C, Arroyo MK (eds) Ecología de los bosques nativos de Chile. Editorial Universitaria, Santiago, Chile, pp 335–362

Lara A, Soto D, Armesto J, Donoso P, Wernli C, Nahuelhual L, Squeo F (eds) (2003) Componentes científicos clave para una política nacional sobre usos, servicios y conservación de los bosques nativos chilenos. Iniciativa Científica Milenio de Mideplan, Universidad Austral de Chile, Valdivia, Chile

Le Roux JP, Elgueta S (2000) Sedimentologic development of a Late Oligocene–Miocene forearc embayment, Valdivia Basin Complex, southern Chile. Sediment Geol 130:27–44

Little C (2005) Exportación de nitrógeno desde la cuenca de Río Valdivia, Chile. Forestry Engineering M.S. Thesis, Universidad Austral de Chile, Valdivia, Chile

Martínez R, Pino M (1979) Edad, paleoecología y sedimentología del Mioceno Marino de la cuesta Santo Domingo, Prov. de Valdivia. In: Proceedings II Congreso Geológico Chileno, Arica, Chile. Instituto de Investigaciones Geológicas, Tomo 3, pp 103–124

Mella A, Kühne A (1985) Sistemática y descripción de las familias, asociaciones y series de suelos derivados de materiales piroclásticos de la zona central-sur de Chile. In: Tosso J (ed) Suelos volcánicos de Chile. INIA, Santiago, Chile, pp 549–716

Moore RB, Johnston CM, Robinson KW, Deacon JR (2004) Estimation of total nitrogen and phosphorus in New England streams using spatially referenced regression models. Scientific Investigations Report 2004–5012. U.S. Department of the Interior, U.S. Geological Survey, Pembroke, New Hampshire, USA

Otero L, Contreras A, Barrales L (1994) Efectos ambientales del reemplazo de bosque nativo por plantaciones (Estudio en cuatro microcuencas en la provincia de Valdivia). Ciencia e Investigación Forestal 8:252–276

Oyarzún CE, Huber A (2003) Nitrogen export from forested and agricultural watersheds of southern Chile. Gayana Bot 60:63–68

Peña H (1999) Dirección General de Aguas 1969–1999, 30 años. Editorial Ponce de León y Escobar, Santiago, Chile

Pérez CA, Hedin LO, Armesto JJ (1998) Nitrogen mineralization in two unpolluted old-growth forests of contrasting biodiversity and dynamics. Ecosystems 1:361–373

Pezoa L (2003) Recopilación y análisis de la variación de las temperaturas (período 1965–2001) y las precipitaciones (período 1931–2001) a partir de la información de estaciones meteorológicas de Chile entre los 33° y 53° de latitud Sur. Forestry Engineering Thesis, Universidad Austral de Chile, Valdivia, Chile

Putuhena W, Cordery I (2000) Some hydrological effects of changing forest cover from eucalyptus to *Pinus radiata*. Agric For Meteorol 100:59–72

Quinn P, Beven KJ, Lamb R (1995) The ln(a/tanβ) index: how to calculate it and how to use it within the TOPMODEL framework. Hydrological Processes 9:161–182

SERNAGEOMIN (Servicio Nacional de Geología y Minería) (ed). (1998) Estudio Geológico-Económico de la X Región Norte. Geología Económica, Recursos minerales y energéticos. Informe Registrado IR-98–15. Servicio Nacional de Geología y Minería, Subdirección Nacional de Geología, Santiago, Chile

Sokal RR, Rohlf FJ (1995) Biometry. 3rd edn. WH Freeman & Company, New York, USA

Soto D, Lara A (2001) Valoración alternativa de los bosques nativos como proveedores de servicios ecosistémicos a los ambientes acuáticos. In: Primack R, Rozzi R, Feinsinger P, Dirzo R, Massardo F (eds) Elementos de Conservación Biológica: Perspectivas Latinoamericanas. Fondo de Cultura Económica, Ciudad de México, México, pp 295–297

Stockner JG, MacIsaac EA (1996) British Columbia lake enrichment programme: two decades of habitat enhancement for sockeye salmon. Regul Rivers Res Manage 12:547–561

Stockner JG, Shortreed KRS (1978) Enhancement of autotrophic production by nutrient addition in a coastal rainforest stream on Vancouver Island. J Fish Res Board Can 35:28–34

Strayer DL, Beighley RE, Thompson LC, Brooks S, Nilsson C, Pinay G, Naiman RJ (2003) Effects of land cover on stream ecosystems: roles of empirical models and scaling issues. Ecosystems 6:407–423

Thomas SM, Neill C, Deegan LA, Krusche AV, Ballester VM, Victoria RL (2004) Influences of land cover and stream size on particulate and dissolved materials in a small Amazonian stream network. Biogeochemistry 68:135–151

Universidad Austral de Chile, Pontificia Universidad Católica de Chile, Universidad Católica de Temuco, Geotécnica Consultores (1995) Catastro y evaluación de recursos vegetacionales nativos de Chile. Manual de Cartografía de la Vegetación. Valdivia, Chile

Veblen TT, Kitzberger T, Burns BR, Rebertus AJ (1995) Perturbaciones y dinámica de regeneración en bosques andinos del sur de Chile y Argentina. In: Armesto JJ, Villagrán C, Arroyo MK (eds) Ecología de los bosques nativos de Chile. Editorial Universitaria, Santiago, Chile, pp 169–198

Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, Schlesinger WH, Tilman DG (1997) Human alteration of the global nitrogen cycle: causes and consequences. Issues Ecol 1:1–15

Wetzel RG, Likens GE (1979) Limnological analysis. W.B. Saunders Company, Philadelphia, U.S.A

Yang X, Chapman GA, Young MA, Gray JM (2005). Using compound topographic index to delineate soil landscape facets from digital elevation models for comprehensive coastal assessment. In: Zerger A, Argent RM (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, ISBN: 0-9758400-2-9, pp 1511–1517. http://www.mssanz.org.au/modsim05/papers/yang_x.pdf

Zahradnik P (1981) Methods for chemical analysis of inland waters. Lecture notes for the International Graduate Training Course on Limnology. Limnologishes Institut, Österreichische Akademie der Wissenschaten, Viena, Austria