INCO-CT2004-510739

EPIC FORCE

Evidence-based Policy for Integrated Control of Forested River Catchments in Extreme Rainfall and Snowmelt

Instrument: Specific Targeted Research Project

Thematic Priority: Specific Measures in Support of International Cooperation, Developing Countries, A.2 Rational Use of Natural resources, A.2.1 Managing humid and semi-humid ecosystems

Deliverable 17
Report on basin response for Chile

A. Iroumé, A. Huber and H. Palacios
Universidad Austral de Chile, Chile

Due date of deliverable: Month 30
Actual submission date: Month 30

Start date of project: 1 February 2005 Duration: 36 months

Organisation name of lead contractor for this deliverable: Universidad Austral de Chile

Revision [final]

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

EXECUTIVE SUMMARY

This report summarizes the basin response associated to plantation forestry development in Chile. The study took place in experimental catchments (3 to 90 ha) and large river basins (more than 90 km^2) located between 37º21' and 41º17' south, in central-southern Chile. Water production, peak flows and sediment transport were studied in the experimental catchments analyzing data from rainfall, water level and sediment gauging stations operated directly with the support of the EPIC project. Discharge and precipitation records in the larger river basins were obtained from Dirección General de Aguas and Dirección Meteorológica de Chile. Land use for different time periods were generated during the project using remote images and aero photos.

In small experimental catchments, the reduction of vegetation cover generates increases in runoff and peak discharges, and the biggest effects happen after clearfelling significant proportions of a forest within the catchments. The combined effect of rainfall pattern, catchment size and topography, road density and extent of affected area should also be considered to fully understand and explain the hydrological effects of land use changes in these catchments.

Following clearcutting of the *Pinus radiata* plantation that covered the 79.4% of the La Reina experimental catchment, runoff and peak flows increase both at annual and summer levels. During the first three years of the post-harvesting period, on average a 110% increase in annual runoff occurred and mean peak flows were 32% higher. After 6 years of development of the new *Eucalyptus spp*. plantation established in the La Reina catchment in 2000, this forest is increasingly consuming water and annual runoff has initiated a recovery towards pre-harvesting levels. Comparisons of peak flows at the La Reina catchment for pre and post-harvesting conditions indicate that the percentage change for the 'large' event category (events with rainfall volumes greater than 50 mm) is less than that resulting from both the 'medium' (from 10 to 50 mm) and 'small' (from 5 to 10 mm) event size categories. Nevertheless, peak flow medians for 2006 are still higher than those from the pre-harvesting conditions indicating that peak flow values after the removal of the plantation do not show an initial important increase followed of a gradual diminution tending towards the peak discharge levels of the pre-harvesting condition. Although runoff in La Reina has initiated in 2006 a decrease tending towards the levels of the pre-harvesting condition, this is not yet the case of the peak flows. At the La Reina catchment the relationship between extreme rainfall events exceeding 100 mm in total precipitation (the upper section of the 'Large' event size category) and extrapolation of this relationship to increasingly larger rainfall event sizes does appear to suggest that, at the scale of extreme events, peak flows with return periods exceeding 10 years do not differ considerably for pre and post-harvesting land cover conditions. This result appears consistent with the suppositions regarding peak flows and extreme events and supports the

hypothesis that, as the size of the flood peak increases, the effect of land use becomes less important.

Data from La Reina, Los Ulmos1 and Los Ulmos2 show a decrease in the annual runoff (in percentage of annual precipitation) as the plantations increase their water consumption capacities from about 68% the year after timber harvesting to 36% after 22 years of plantation growth.

In large catchments, annual water reductions associated to afforestation compromising more than 30% of total catchment area have been detected. The highest reduction occurs for $Q_{50\%}$ while $Q_{80\%}$ and $Q_{90\%}$ are much less affected. Since $Q_{80\%}$ and $Q_{90\%}$ are used to define permanent and continuous Water Rights, it is possible that already existing permanent and continuous water rights could be only marginally being affected by the increase of the planted area. However, those eventual water rights, more associated to $Q_{50\%}$, would be the most possible affected.

At the Caramávida, Duqueco and Mulchén river basins the trends of the relationships between rainfall events from pairs of storms (one storm from the pre-plantation development period and one from the post-plantation development period) and the resultant peak discharge values and extrapolations of the relationships to increasingly larger rainfall event sizes do appear to suggest that at the scale of extreme events, the corresponding peak flow values from pre and post-plantation development land cover conditions do not differ considerably. In these three river basins, the differences in peak flow values from pre and post-plantation development conditions only differ for events with return periods lower than 5 years. These results appear consistent with the suppositions regarding peak flows and extreme events and the findings for the smaller experimental catchments. Although, in the large river basins to the effect of the increase of the afforested area it is necessary to add the corresponding to the variations from one period to the other in the intensity pattern of the precipitations that generate these peak flows and to the differences in areal distribution of precipitation among storms and study periods.

In small experimental catchments, the increases in sediment load after clearfelling can be defined as extreme events not necessarily generated by intense rainfalls but associated to road building and clearcutting during final harvest operations. This reinforces the proposals that the EPIC-UACh group, within the framework of best management practices and definition of standards for harvesting and road planning, has been raising in forums and discussion groups

The results presented in this document can be used to provide recommendations regarding forest management options, which allow adequate tree growth rates but are compatible with restrictions on water availability and quality.

CONTENTS

1. INTRODUCTION

1.1. Project Summary and Work Package 3 description

The impact of forest management on extreme floods is an area in which there is considerable scientific uncertainty as well as poorly conceived policy. EPIC FORCE aims to improve the integrated management of forest and water resources at the river basin scale through the development of policies based on sound science, focusing on extreme rainfall/snowmelt events. It will link scientific, management and policy research by:

1) developing a generic model for the impact of management practices on basin response to extreme rainfall;

2) developing improved strategies for integrated forest and water management relevant to extreme events;

3) developing evidence-based policy recommendations for national agencies and for the EU and World Bank.

The focus areas are four Latin American countries (Costa Rica, Ecuador, Chile and Argentina), which represent a range of humid forest and rainfall/snowmelt regimes with major flood and erosion problems and which suffer from a lack of integrated water and forest policies.The generic model will be derived using existing advanced modelling technology and data from the focus areas: it will examine the hypothesis that, as the size of the flood peak increases, the effect of land use becomes less important. The improved management strategies will be developed from reviews of current management and of best practice, from model scenario applications and from field studies. The policy recommendations will be developed by proposing improvements to the basis of existing national policies in the focus countries in the light of the modelling and management studies. Crucial participants will be the national forest and water resource agencies, which will receive the project technologies. EPIC FORCE will improve our understanding of forest ecosystem dynamics (for extreme rainfall events) under human pressure (from logging and forest conversion), allowing a more sustainable use of water and forest resources. It will support the efficient and well-directed use of limited development resources.

Work Package 3 (WP3) is analyzing basin response to forest management for extreme rainfall in central-southern Chile, both in small experimental catchments and large river basins in areas with large scale forest plantation development. The area is characterized by high seasonal and all year rainfall (up to 4000 mm) with large interannual variability from El Niño effects.

The main land use of this area corresponds to exotic, short rotation plantations; where the problem impacts are flooding and soil erosion; water pollution and decreased water yields. Associated with the demands that the certification processes are imposing to large scale forest operations, the Chilean forest companies are requiring best management practice guidelines, while other needs are improved integrated forest (both plantation and native) and water management legislation.

1.2. Plantation forestry at a global scale

By the year 2010, some 5.55 billion hectares of forestlands will be required to satisfy the predicted needs for forest and wood products, carbon sequestration and biodiversity conservation (Lund and Ireminger, 1999). These total forestland needs are by 1.38 billion hectares above the 1994 forest existence. The results of global supply and demand analysis suggest that demand for wood will continue to increase for the foreseeable future, due to continued increases in population and income (FAO, 2000). However, during the past thirty years, natural forest resources have declined in a number of countries as forests have being cleared, degraded, or withdrawn from production (particularly in the area of natural forest available for wood supply). This trend is expected to continue in the future specially because the use of natural forests for wood production is being increasingly opposed by environmental and preservationist groups, who are pressing to retain the remaining natural forests of the world in their natural state (Sutton, 1999).

This suggests that future demand will have to be supplied from a diminishing, or more restricted, forest resource base. In other words, the burden placed on the remaining forests to produce wood will increase commensurately. To solve this dilemma the only solution is to increasingly shift the wood harvest from natural forests to deliberately created planted forests (Sutton, 1999).

Forest plantations account for a small proportion of the global forest area. It is estimated that in 1995 the global area of forest plantations was about 123.7 million hectares (approximately 3.5 percent of the global forest area) to then reach some 187 million hectares after increasing at an annual rate of 14 million hectares between 1990 and 2000 (FAO, 2000; IUFRO, 2005).

The solution of moving to planted forests for wood production as many attractions, as it leaves the remaining natural forests to be managed for their nonwood-producing objectives. Plantation forests will not be asked to meet high demands for biodiversity, for species or age diversification and for the use of only indigenous species (Sutton, 1999), although they will certainly require being responsibly managed with respect to the environment as they are capable of deliver both multiple-habitat forests and productive tree crops (IUFRO, 2005).

A key factor of plantation expansion is going to be economics, as planted forests are probably the most capital-intense industry in existence (Sutton, 1999). Other factors than could constrain additional development of planted forests are environmental issues, e.g., concerns about biological risks especially when they are managed as even-aged monocultures, and scarcity of suitable land for new planting because large parts of the remaining available land is unsuitable for plantation forestry (altitude, slope, fertility, salinity, water table and aridity constraints) or, more frequently, because is more valuable in alternative uses such as agriculture, urban development or industry. In addition the hydrological effects of large scale afforestation and deforestation and water allocation issues could further constrain the development of planted forests. As an example, the South African White Paper on Forestry (DWAF, 1996) notes *"Controversy about the effects of afforestation on water supplies began in the 1920s, and continues today. This led to the implementation of controls on afforestation that have been applied since 1972 through the afforestation permit system. In 1986 the industrial forests in South Africa were estimated to consume about 1.2 billion cubic meters of water that would otherwise have entered rivers and streams, and been available for other uses. This volume equated to about 30% of the amount used for urban and industrial purposes, or about one tenth the volume used in irrigated agriculture. The water consumed is a cost required to support the forestry sector as a contributor to our economy."*.

1.3. Plantation forestry in Chile

In Chile, the forest sector participates with the 3.4% of the national GDP and the 8.8% of total exports (INFOR, 2005). In the country, plantation forestry based on introduced Monterey pine (*Pinus radiata* D.Don) and *Eucalyptus spp.* is very important, and near the 90% of the Chilean forest economy comes from plantations that cover the 3% of the national territory and correspond to the 13% of the forest lands. These plantations have grown in area from some 300 thousand hectares at the beginning of the 1970s to 2.1 million hectares in 2004 and are established as evenaged stands where *Pinus radiata* (Monterey pine) and *Eucalyptus spp.* represent the 68 and 24%, respectively, of these man made forests (INFOR, 2006; CORMA, 2007).

The importance of the economic role of the forest sector is likely to increase. Forestry has a real opportunity for expansion in the country associated to the economic revenue of plantation forests, the existence of some 2 million hectares of uncovered plantable lands, from which 500 thousand hectares are due to be planted in this decade (CORMA, 2007), and the existing 4.5 million hectares of potentially productive native forests (CONAF-CONAMA, 1999).

The Chilean commercial forests are distributed between 34º and 41º30’ south (see Figure 1), in areas with Mediterranean influence where annual rainfalls vary from 1000 mm in the north to near 3000 mm in some southernmost sites (Iroumé, 2005). Precipitations are highly concentrated in winter with summer dry periods that last up to 6 months in the Sixth, Seventh, Eighth and northern Ninth Regions (between 34° and 38°30’ south) and about 2 to 3 months in the southern part of the Araucania and up to the Los Lagos Regions (38°30’ to 41°30’ south), Romero (1985).

Figure 1. Areal distribution of plantation forestry in Chile.

Besides the economic importance, afforestation with fast growing exotic species has ended up being less social and politically accepted because the supposed impact on the environment and water resources (Gross and Hajek, 1998; Hofstede *et al.*, 1998; Toro and Gessel, 1999).

1.4. Hydrological consequences of intensive forest operations

The hydrological consequences of intensive forest operations on water yield and quality have received much attention (Cameron, 2003; MacDonald and Stednick, 2003; Andréassian, 2004; Brown *et al.* 2005; Sun *et al.* 2006). According to Calder (1992), at a global scale afforestation and deforestation are the most important land use changes in terms of hydrological effects. Deforestation tends to generate net erosion and nutrient losses. Afforestation tends to reduce groundwater recharge and net water availability because the trees intercept part of the precipitation and, owing to their deeper root system, transpire more water than grasses during the drier periods.

Although the establishment of plantations on land previously in pasture or under cultivation has protected many areas from further erosion (Fahey, 1994; Uriarte, 1994), large scale forest operations can severely affect water, nutrient, and sediment cycling within a catchment (Calder, 1992; Keenan and Kimmins, 1993; Rowe and Pearce, 1994a, b; Rowe and Taylor, 1994; Stednick, 1996). The establishment of plantations initiates long-term changes that modify the distribution of precipitation and its chemistry, and affects soil moisture patterns, water yield, and water quality. Final felling operations remove the canopy and water yield returns to near pre-establishment conditions, but the effects of logging and transportation generate massive soil and landscape alterations leading to increases in generated runoff and larger amounts of sediment delivered into streams.

Rainfall interception by the canopy dominates water yield in areas with medium-to-high annual rainfall (Fahey, 1994) while throughfall and stemflow are the main sources of soil water for any forest, stemflow being especially important for supporting the growth of individual trees in areas of low rainfall (Voigt, 1960; Price, 1982; Huber and Oyarzún, 1983). The amount of precipitation reaching the soil surface depends on the type and density of the vegetation cover. This cover intercepts part of the incoming precipitation so that it is temporarily stored on the leaves, branches and trunks from where it can evaporate (Ward and Robinson, 1989).

Evaporation rates of water intercepted by forest canopies exceed potential evaporation rates from free water surfaces (Ward and Robinson, 1989). This is because, owing to the rougher surface, the aerodynamic resistance of the vegetation cover is lower than that of water surfaces. As part, if not the whole, of such interception losses represent an addition to net catchment evaporative losses, this process may dominate water availability (Fahey, 1994).

Owing to the recognised effect of evaporation losses on water balances and water availability, quantification and modelling of the interception process has generated great attention. Studies of these rainfall redistribution processes include those of Aussenac (1969), Cornet (1977), Aussenac and Boulongeat (1980), Aussenac (1981), Howard (1972), Crockford and Richardson (1990a, b, c, d; 2000), Neal *et al.* (1991; 1993), Pook *et al.* (1991a, b), Kelliher *et al.* (1992), Myers and Talsma (1992), Stogsdill *et al.* (1992), Viville *et al.* (1993), Buttafuogo *et al.* (1994), Fahey (1994), Rowe and Pearce (1994a, b), Tiktak (1994), Haydon *et al.* (1996), Iovino *et al.* (1998) and Aboal *et al.* (1999). Among the interception modelling studies, those by Rutter *et al.* (1971/1972; 1975; 1977), Loustau *et al.* (1992), Lankreijer *et al.* (1993; 1999), Gash *et al.* (1995), Whelan and Anderson (1996), Davie and Durocher (1997a, b), Valente *et al.* (1997), Aboal *et al.* (1999), Schellekens *et al.* (1999) and Jackson (2000) are prominent.

Regarding runoff, Troendle and King (1987), Stonemam and Schofield (1989), Ruprecht *et al.* (1991), Cornish (1993), Ruprecht and Stonemam (1993), David *et al.* (1994), Bari *et al.* (1996), Lane and Mackay (2001), Swank *et al.* (2001), Andréassian (2004) and Brown *et al.* (2005) showed that after timber harvesting -and even after intense thinning- annual streamflow increases from pre-harvesting conditions. Changes in streamflow after timber harvesting occur when more than the 20% of the forest cover is reduced (Stednick, 1996), annual runoff increases between 10 to 120% depending on the extension of the clearcut area (Keppeler and Ziemer, 1990; Zimmerman, 1992; Fahey, 1994; Dye and Poulter, 1995; Swank *et al.*, 2001) and the effect is noticeable only the first years after final harvest (David *et al.*, 1994; Bari *et al.*, 1996), or up to 12-15 years (Ruprecht and Stoneman, 1993).

The effects of forests on summer flows is even greater (Harr, 1976; Swanson and Hillman, 1977; Harr *et al*., 1979; Helvey, 1980; Swift and Swank, 1981; Keppeler, 1986; Keppeler and Ziemer, 1990; Calder, 1992; Fahey, 1994; Keppeler, 1998; Dye, 2000; Jones and Swanson, 2001; Cassie *et al*., 2002; Gush *et al*., 2002, Andréassian, 2004; Brown *et al.*, 2005), because interception and transpiration capacity are at the highest levels during summer months, because forests are in full vegetative period and fully leaved. The characteristics of the rains during this period (less frequent, less intense and of smaller totals compared for example with those of winter) further favour interception capacity, reducing again the quantity of water that reaches the soil surface (Iroumé and Huber, 2000). Higher transpiration losses because of the deeper root systems of trees reduce soil water reserves which sustain base flows during summer (Calder, 1992).

Peak flows also increase after timber harvesting (Fahey, 1994; Jones and Grant, 1996; Thomas and Megahan, 1998; Beschta *et al.*, 2000; Caissie *et al.*, 2002). Increases only for small events have been reported by Whitehead and Robinson (1993), Ziemer (1998) and Caissie *et al.* (2002), in a range between 14 and 48% by Harr *et al.* (1979), Fahey (1994) and Swank *et al.* (2001) while Jones and Grant (1996) found 50 and 100% increase in peak flows for small and large catchments, respectively. The effect of storm type is still controversial as Smith (1987) found that timber harvesting affects storms of 100-year return periods whereas Whitehead and Robinson (1993) reported no significant differences on flood peaks from forested and grassland catchments for large events. La Marche and Lettenmaier (2001) and Beschta *et al.* (2000) reported peak flow increases after timber harvesting for 5- and 10-year recurrence interval events while Thomas and Megahan (1998) did not detect any change for flows having return intervals larger than 2 years.

Magnitude and duration of post-harvesting effects on base and peak flows depend on soil type, hillslopes steepness aspect and lithology of the catchment, rainfall quantity, frequency and intensity, as well as on extension and type of forest operations and characteristics of the vegetation that re-establishes after the harvesting. Flow increase is proportional to harvested area in the catchment (Hibbert, 1967), is more pronounced after clearcuttings than partial harvestings (Rothacher, 1970; Fahey, 1994) and more significant in wet temperate regions (Keppeler, 1998). Major effects occur up to three years after logging. Afterwards, because of vegetation regrowth, streamflow quickly returns to baseline levels (Fahey, 1994; Keppeler, 1998; Ruprecht and Stoneman, 1993).

Rainfall chemistry is modified during its interaction with the components of the ecosystem, in which meteorological, biological and geological fluxes exchange with the water flow, and this results in different stream water chemistry (Uyttendaele and Iroumé, 2002). Throughfall and stemflow chemistry are modified mainly through the processes of wash off of materials that were deposited during the preceding period without rain and leaching of nutrients from plant tissues and canopy interactions (Potter *et al.*, 1991). Net rainfall (stemflow and throughfall) chemistry in coniferous and long leafed forest types can differ due to different dry deposition amounts on the canopy surface and its quality (Rapp, 1969), plant tissue composition (Cronan and Reiners, 1983), bark roughness (Edmonds *et al.*, 1991), the accompanying vegetation (Denison, 1973; Oyarzún *et al.*, 1998) and associative wildlife.

Many studies show that one of the most important water quality problem associate with forestry is sedimentation (Beasley and Granillo, 1988; Binkley and Brown, 1993; Ensign and Mallin, 2001). Harvesting and site preparation techniques that expose bare soil to the erosional influence of raindrops have the greatest potential to impact water quality and reduce soil productivity. Areas where soil has been disturbed are subject to erosion resulting in the downslope movement of sediment after it rains (National Council for Air and Stream Improvement, 1994). Sources of sediment include roads, bare soil on steep slopes, cutbanks, slope failures and debris flows, and streambank erosion and channel scour. The construction and use of roads, skid trails and landings for access to and movement of logs, particularly in steeper areas, are harvesting activities with the greatest erosion potential (Brown and Binkley, 1994). Extensive vehicle movement removes vegetation and litter cover, and disturbs mineral soils, increasing chances of overland flow, stormflows and runoff with high erosive forces (Patric, 1978; McMinn, 1984; Gayoso and Iroumé, 1995).

Sedimentation impacts from forestry operations are generally short-lived. Major impacts occur during and for a few years after harvesting operations, until the vegetation re-establishes and road surfaces and cut and fill slopes stabilize. Careful location and layout of roads and logging operations and proper planning and use of best management practices (BMPs) can lessen soil losses by up the 50% and greatly reduce the magnitude of sedimentation effects (Yoho, 1980; Stringer and Thompson, 2000).

1.5. Forest and water issues research in Chile

Forest operations are the most significant land-use changes in terms of their hydrological effects (Calder, 1992), and although Bathurst *et al*. (1998) have analyzed the impacts of the replacement of native forests by exotic plantations on water yield, in Chile the main hydrological effects arise from the afforestation of uncovered lands, the type of harvesting techniques (large scale clearcuttings) and the intense interventions that take place at the end of the growing cycle in short rotations (22-24 years in Monterey pine and 10-12 years in eucalyptus plantations), in environments characterized by abundant and intense rainfalls in winter and dry summers (Iroumé *et al*., 2005).

In the driest months, water availability reductions associated with large scale plantation developments have been generating concern among public opinion and interest and environmental groups. This cover type is in full growing period with interception and transpiration rates at their highest potential. Problems are occurring in drinking and irrigation water supply catchments and where ground water table depletions are affecting water availability in farms and rural settlements.

Some studies relating forests and waters have taken place in Chile. The impacts of forest operations on soil properties were considered by Gayoso and Iroumé (1984; 1991a, b). Data obtained from researches related to rainfall canopy interception, soil moisture changes and evapotranspiration processes can be found in Huber and Oyarzún (1983; 1990; 1992), Huber *et al.* (1985), Huber and López (1993), Caldentey and Fuentes (1995), Huber and Martinez (1995), Iroumé and Huber (2000; 2002) and Huber and Iroumé (2001) and Huber *et al.* (2007). Water yield and sediment delivery at a catchment scale were studied by Iroumé (1990; 1992; 2003), Mayén (2003), Lenzi *et al*. (2004), Olivares (2003), Primrose (2004) and Uyttendaele (2006, while Bathurst *et al*. (1998) presented long-term simulations of the impacts on water yield of the replacement of native forests by exotic plantations.

Results on increases in runoff and peak flows after timber harvesting were presented in Mayén (2003), Primrose (2004) and Iroumé *et al.* (2005, 2006). In these studies, the results of analysis of runoff and peak flows registered in pre- and post-harvesting periods and from catchments with different forest cover are compared.

Some studies of throughfall and stemflow chemistry in forests were undertaken in southern Chile (Oyarzún *et al.*, 1998, Godoy *et al.*, 1999, Uyttendaele and Iroumé, 2002). These studies describe changes of rainfall chemistry in native coniferous and broadleaved forests and *Pinus radiata* plantations. Monitoring mass balances in southern Chile is important since current deposition chemistry gives evidence of low anthropogenic influences compared to some Northern Hemisphere regions and reflects one of the closest approximations of pre-industrial atmospheric conditions of the world (Weathers and Likens, 1997; Galloway *et al.*, 1996). Moreover, few studies have been carried out in the Southern Hemisphere, especially where there is little pollution (Likens *et al.*, 1987; Hedin *et al.*, 1995; Galloway *et al.*, 1996). Studies of nutrient cycling in these 'clean' sites would enhance understanding of altered nutrient cycling in polluted areas. Furthermore, this monitoring would alert us to the anticipated increased nutrient deposition, especially for nitrogen (Galloway *et al.*, 1994).

Erosion processes in forest environments have been studied using experimental plots by Stolzenbach (1998) and Rivas (2000), and more recent results with the application of the $^{+7}$Be technique are reported by Iroumé *et al*. (2004) and Schuller *et al*. (2004, 2006).

These studies have contributed to our knowledge of the role of the forests in hydrological processes, enabling predictions of the environmental impacts of forest operations and assisting management of water resources. Chilean water resource managers, the water and environmental regulatory authorities, and public opinion have all become aware of the impacts of afforestation and deforestation on water yield and water quality wherever large-scale forest operations are concentrated. In order to be competitive in international markets, forest companies must certify their products. In 2006, about 370,000 and 1.2 million hectares of plantation forests are certified by Forest Stewardship Council and ISO 14001 standards systems, respectively (CORMA, 2007; FSC, 2007). Through these standards forest companies are committed to adopt best management practices (BMPs) to reduce or mitigate their environmental impacts, so that the quantification and the monitoring of BMP effects on water quantity and quality, erosion and sediment transport become relevant.

2. DESCRIPTION OF PROJECT FOCUS BASINS

2.1. The study area

The study takes place in experimental catchments and large river basins located within the Biobío and Los Lagos Regions (latitudinal range between 37º21' and 41º17' south), in central-southern Chile, Figure 2.

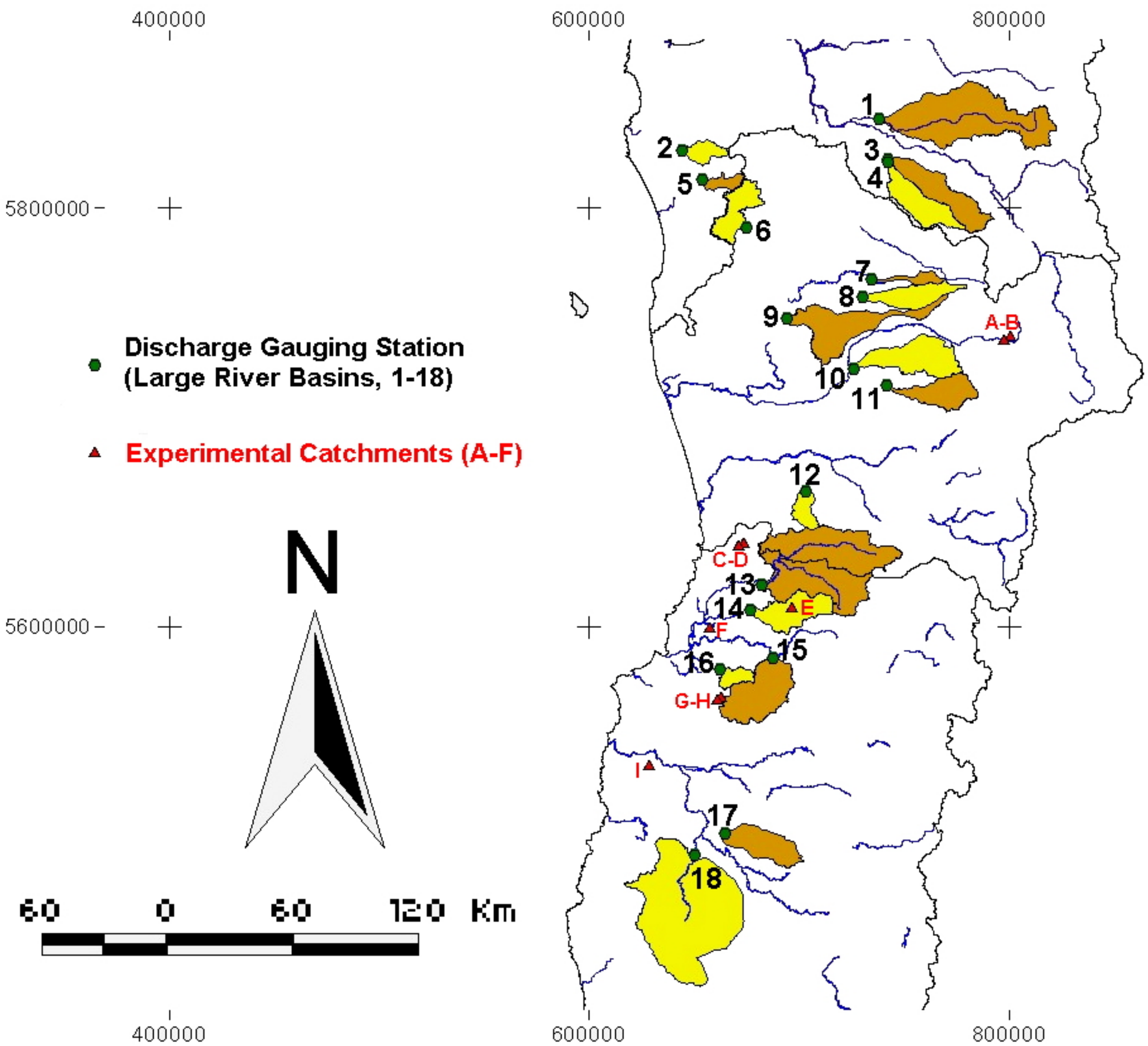


Figure 2. Location of experimental catchments (in red) and large river basins (brown and yellow and numbers in black) within the study area.

The northern part of the Bíobio Region, from the coast to the Andes Mountains, has a warm temperate climate with a dry season of 4 to 5 months (DMC, 2006). Mean temperatures are below 13°C, with 12°C of annual thermal amplitude and 13°C of daily oscillation, values that are lower in the costal area and that increase toward the east. Mean annual precipitations are over 1000 mm, but in the higher Andes Mountains precipitation is characterized by snow fall and surpasses 3000 mm/year. Cumulative rainfall for the rainy months (May to August) is less than the 70% of the annual total, being the dryer period from December to March with monthly totals lower than 40 mm.

Most of the Bíobio Region (from the coast to the Andes Mountains) and the intermediate zone of the Araucania Region (up to the 39º south) have a warm temperate climate with a dry season of less than 4 months. In the Bíobio Region annual precipitations vary from 1000 mm to the east of the Costal Mountain Range to more than 3000 mm in the Andes Mountains (most of it is snow), while in the Araucania Region annual totals exceed 2000 mm. Precipitation from May to August equals the 65 to 70% of annual total. Precipitation in summer (December to February) is 5 to 6% of annual totals, which indicates that the precipitation in spring and fall is still important. In the Bíobio Region mean temperatures are lightly lowers than those from the northern part: Diguillín presents 1°C less than Chillán, difference that also occurs in the coast with values which are 1°C or 2°C lowers than in the central valley. The influence of the vicinity of the ocean is noticed in the variations of annual thermal amplitude: 7.5°C in Concepción, 10.3°C in Diguillín and 11.4°C in Coihueco. In the Araucanía Region the thermal regime registers an oscillation of 5°C with a mean annual temperature of almost 12°C, a mean temperature of the coldest month of 8°C and with 15°C in the warmest (DMC, 2006).

The southern coastal area of the Bíobio Region, most of the Araucanía Region and the Los Ríos and Los Lagos Regions have rainy temperate climate with Mediterranean influence. In the Bíobio Region this climate specifically occurs in the province of Arauco, zone influenced by the presence, to the east, of the higher elevations of the Cordillera de Nahuelbuta. Precipitation increases from the Bíobio Region to the south, having Contulmo 140 mm more than in Concepción which is located 170 km more towards the north. In the Araucanía Region precipitations are over 1000 mm/year and occur all year round, with a lower decrease during the summer months. In the Los Rios and Los Lagos Regions annual precipitations are over 2500 mm in the western slopes of the Costal Mountain range (Corral and Niebla), to then decrease to less than 1900 mm in Valdivia (Pichoy weather station) and 1330 mm in Osorno (in the central valley) and increase again to more than 2500 mm towards the Andes Mountains (DMC, 2006). In the Bíobio Region annual thermal amplitude is low (in the order of 8°C from the Contulmo records), reaches important values in the longitudinal valleys and the lower Andes areas of the Araucania Region due to the distance to the coast and its higher continental characteristics, and is moderate in the Los Ríos and Los Lagos Regions by the presence of numerous lakes that help to maintain a thermal homogeneity.

Seven major river basins are comprised in the study area. From north to south they are: Itata (11040 km^2), Biobío (24029 km^2), Imperial (12054 km^2), Toltén (7886 km^2), Valdivia (11119 km^2 with the 90.8% in Chile and the 9.2% in Argentina) and Bueno (17210 km^2). The flow direction of the main rivers is from east to west, from the Cordillera de Los Andes towards the Pacific Ocean (IGM, 1983).

In the inter-fluvium of these main basins, several important rivers develop from the Central valley or the Coastal Range of Mountains to discharge into the Pacific Ocean. These river basins have pluvial regimes and their runoff increases from north to south associated to the increase in precipitation.

Itata and Biobío are the most meridional rivers of the hydrographic region known as "rivers of mix torrential regime in the sub humid zone of Chile" (IGM, 1984). These rivers are characterized by a torrential regime with pluvial peak flows in winter and snowmelt high flows in spring and early summer, and a pronounced low flow period in autumn.

Rivers Imperial, Toltén, Valdivia and Bueno belong to the hydrographic region of the "quiet rivers regulated by lakes of the humid zone of Chile" (IGM, 1984). With the exception of the Imperial River in the other river basins lakes developed during the quaternary glaciation closed by moraines located between the Andes and the central valley. These lakes generate a runoff discontinuity because the rivers upstream the lakes have torrential regimes with pluvial peak flows in winter and snowmelt high flows in spring and early summer, while those flowing downstream are quitter and even navigable.

2.2 Description of experimental catchments

Water production, peak flows and sediment transport are been studied in nine experimental catchments, whose locations can be seen in Figure 2 (experimental catchments A to F, in red) and in more detail in Figure 3.

Figure 3. Location of the experimental catchments.

The Rio Tres Arroyos and Piedra Santa catchments (5.93 and 2.88 km^2) are located on sandy soils in the Andes Mountains in the area of the Malalcahuello Forest Reserve (38°25.5'-38°27' S and 71°32.5'-71°35' W). Part of the annual precipitation falls as snow but runoff regime in these two catchments is dominated mainly by rainfall with little snowmelt participation.

The other seven experimental catchments (Aragón1, Aragón2, Pumillahue, Los Pinos, Los Ulmos1, Los Ulmos2 and La Reina) have between 89.8 and 2.9 ha, are all located on the Coastal Range of mountains on red clayed soils under forest plantation activities. All these experimental catchments have pluvial regimes.

Main physiographic, soil and land use characteristics at the experimental catchments are summarized in Tables 1 and 2, while digital elevation models (DEM) of selected experimental catchments are shown in Figure 4.

Table 1. Main physiographic characteristics of the studied experimental catchments.

Catchment		Area	Drainage density	Mean hillslope	Altitude range	Road Density	Soils
Number[a]	Name	ha	m ha^{-1}	%	m.a.s.l.	m ha^{-1}	
A	Tres Arroyos	593.00	15.7	39.0	1095-1856	no	Sandy soils derived from volcanic ashes.
B	Piedra Santa	287.70	28.4	31.7	990-1705	1.5	Sandy soils derived from volcanic ashes.
C	Aragón 1	17.80	15.9	31.0	30-270	8.8	Red clayed soils generated from volcanic ashes deposited on metamorphic schists.
D	Aragon 2	8.00	4.1	36.0	30-270	19.6	As in Aragón1
E	Pumillahue	2.94	22.4	21.0	99-153	0	Red clayed soils generated from volcanic ashes deposited on metamorphic mica-schists.
F	Los Pinos	89.80	43.8	7.6	114-224	20	Derived from volcanic ashes of intermediate to modern age, deposited on metamorphic rocks. Considered as a transition from loamy to red clayed soils.
G	Los Ulmos1	10.80	165.1	12.0	175-230	139	Red clayed originating from old volcanic ashes deposited on the coastal metamorphic complex.
H	Los Ulmos2	16.10	58.9	20.6	155-210	87	As in Los Ulmos1.
I	La Reina	34.35	78.8	23.7	35-225	12	Transition from those originating from old volcanic ashes deposited on volcanic conglomerates and those derived from old clays sedimented on volcanic andesitic and basaltic formations.

[a] Referred to Figure 2.

Table 2. Land use at the experimental catchments.

Catchment	Land uses
Tres Arroyos	79% covered by broadleaved native forests, the remaining 21% are sandy volcanic ashes above the vegetation limit.
Piedra Santa	56% broadleaved native forest, the remaining 44% is grasslands and shrubs used for cattle rising.
Aragón1	87.3% of catchment area covered with *Pinus radiata* plantations established in 1989, clearcut between last days of April and July 2005 (winter). Riparian vegetation and roads correspond to 6.2% (1.1 ha) and 0.9% (0.16 ha) respectively.
Aragon2	90.5% of catchment area covered with *Pinus radiata* plantations established in 1993, 9.5% (0.77 ha) riparian vegetation and roads. No forest operations during the study period.
Pumillahue	Second growth forest where *Nothofagus oblicua* corresponds to 78% of total basal area. Accompanying species are *Persea lingue*, *Laurelia sempevirens* with a few *Lomatia hirsuta* and *Aextoxicum punctatum* trees. Understory formed by *Chusquea quila*, *Nertera granadensis* and *Aristotelia chilensis*.
Los Pinos	33% of catchment area covered with adult *Pinus radiata* plantations established between 1976 and 1982, 40% are grasslands and 27% riparian vegetation. No forest operations during the study period. Forested area corresponds to 73% of total catchment area. Grasslands are continuously been transformed into natural regenerated second growth native forests
Los Ulmos1	81% of catchment area covered with *Eucalyptus nitens* plantation established in 1997 with 1,600 trees/ha. The remaining 19% of the area corresponds to roads and riparian vegetation, 19%.
Los Ulmos2	From the total catchment area, 45% is covered with *Eucalyptus nitens* (7.3 ha) and 23% with *Pinus radiata* (3.7 ha) forests planted in winter (June-July) 2000. Roads, riparian vegetation and several stands of different species account for the remaining 32% of the catchment area.
La Reina	79.4% of catchment area covered with *Pinus radiata* plantation established in 1977 and clearcut and replaced by a *Eucalyptus nitens* forest planted in winter (June-July) 2000. Roads and riparian vegetation correspond to 20.6%.

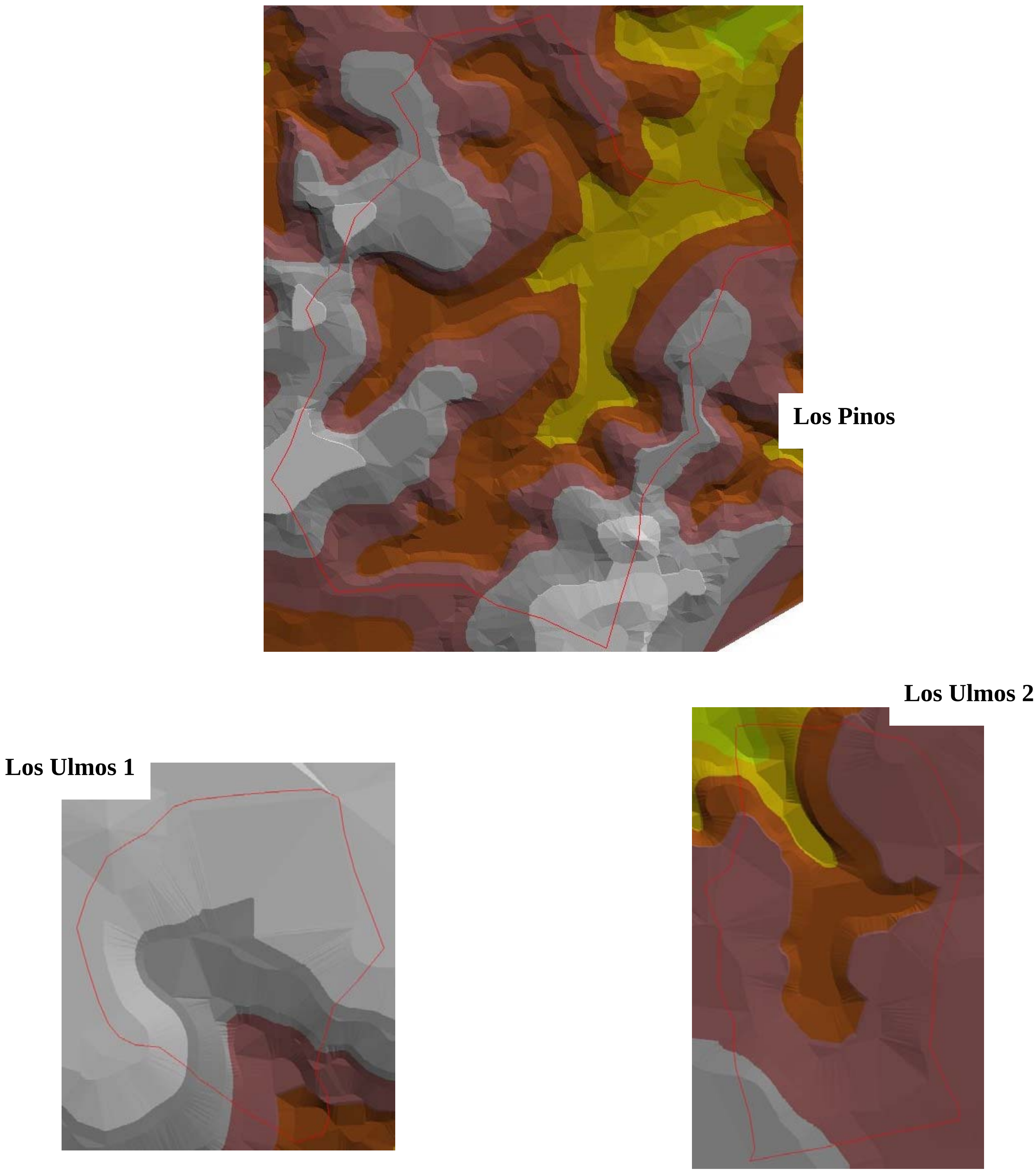


Figure 4. Digital elevation models (DEM) of selected experimental catchments.

2.3 Description of large river basins

Water production and peak flows are studied in eighteen large river basins located in areas where plantation forests are distributed (see Figure 2). In this figure, the river basins are numbered from north to south and the names of the rivers associated to this list are presented in Table 3.

Table 3. Large river basins and discharge gauging stations.

River basin		Discharge gauging station	
Number[a]	Name	Name of location	Controlled catchment area km^2
1	Duqueco	Cerrillos	1545
2	Caramávida	Caramávida	94
3	Bureo	Mulchén	567
4	Mulchén	Mulchén	434
5	Butamalal	Butamalal	118
6	Purén	Tranamán	354
7	Traiguén	Victoria	106
8	Quino	Longitudinal	344
9	Quillén	Galvarino	734
10	Muco	Puente Muco	650
11	Quepe	Vilcún	386
12	Puyehue	Quitratúe	138
13	Cruces	Rucaco	1740
14	Iñaque	Máfil	424
15	Collilelfu	Los Lagos	581
16	Santo Domingo	Rincón de la Piedra	127
17	Damas	Tacamó	408
18	Negro	Chahuilco	2318

[a] Referred to Figure 2

Land uses for selected river basins (Duqueco, Caramávida, Mulchén, Quillén, Muco and Quepe) for different time periods, are presented in Figures 5 to 10. A summary of the land uses considering the categories “native forests”, “plantation forests”, “agriculture” (both grasslands and crop or cultivated lands) and “others” (urban areas or zones without vegetation cover) for these six river basins is included in Table 4 .

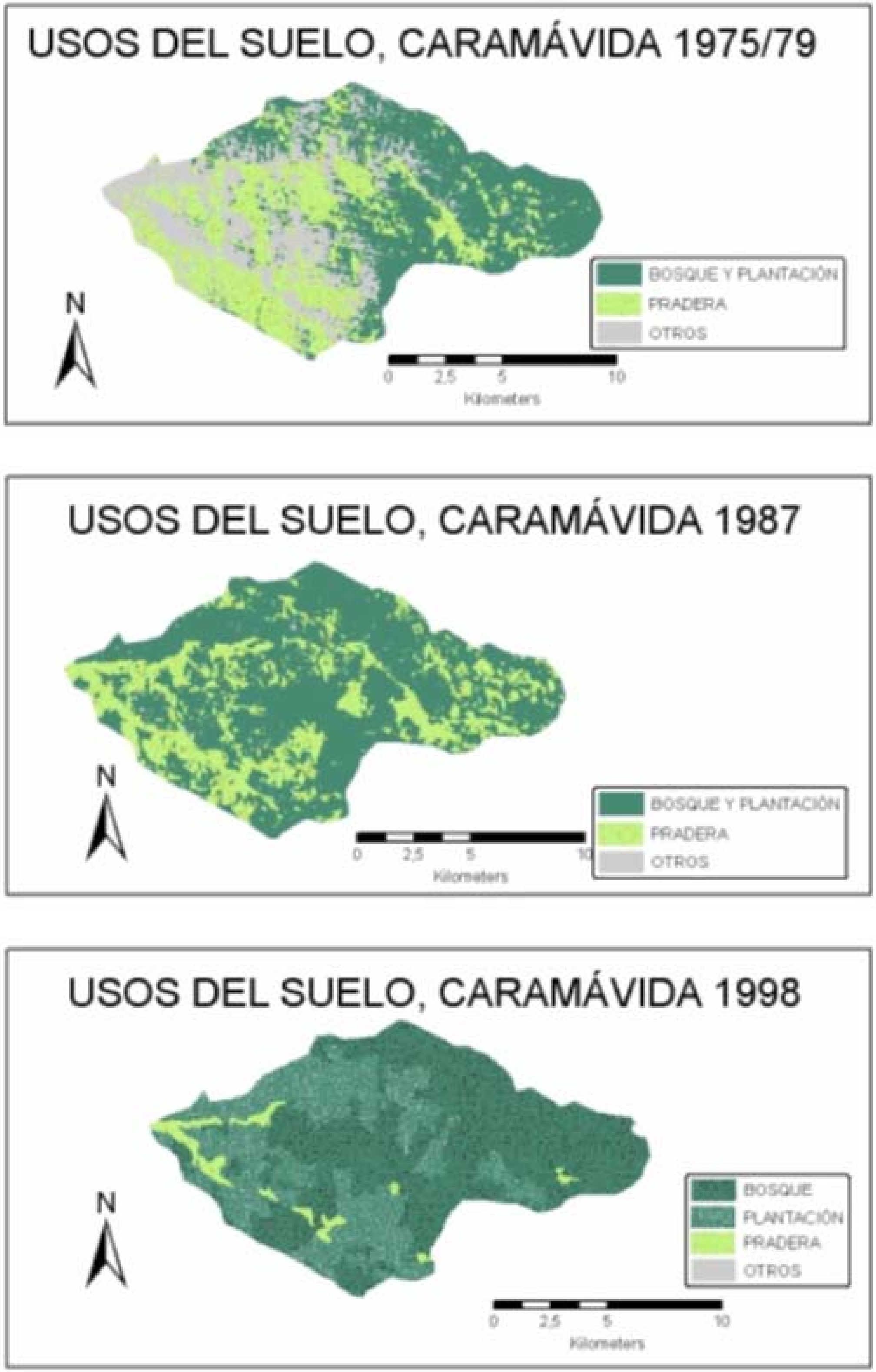
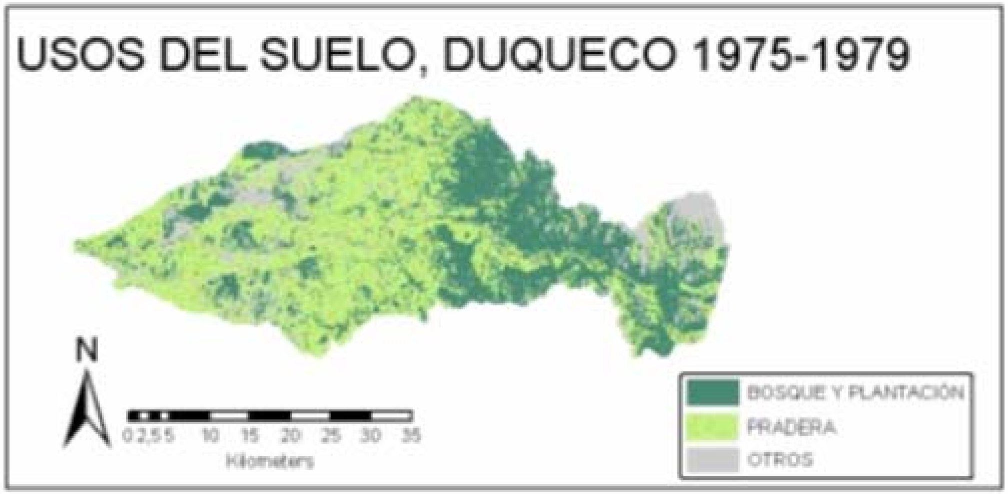
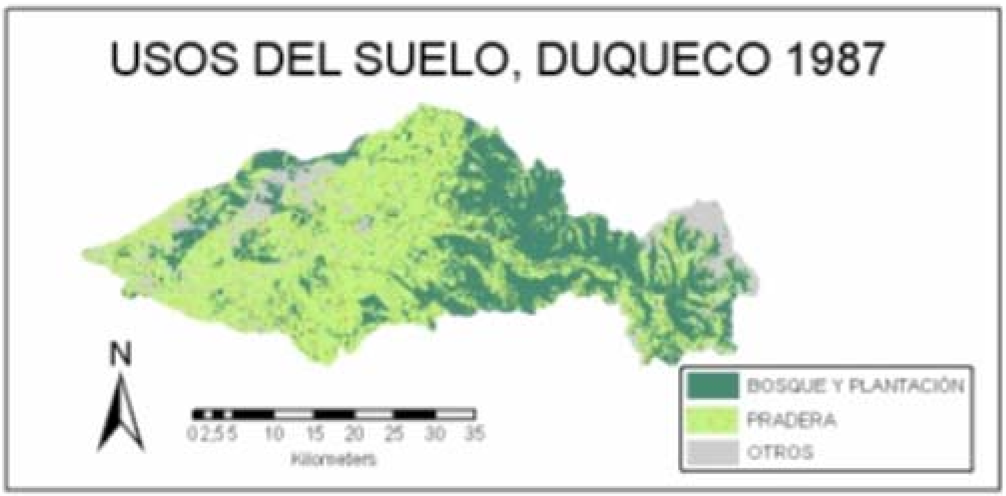


Figure 5. Land uses at Caramávida river basin.





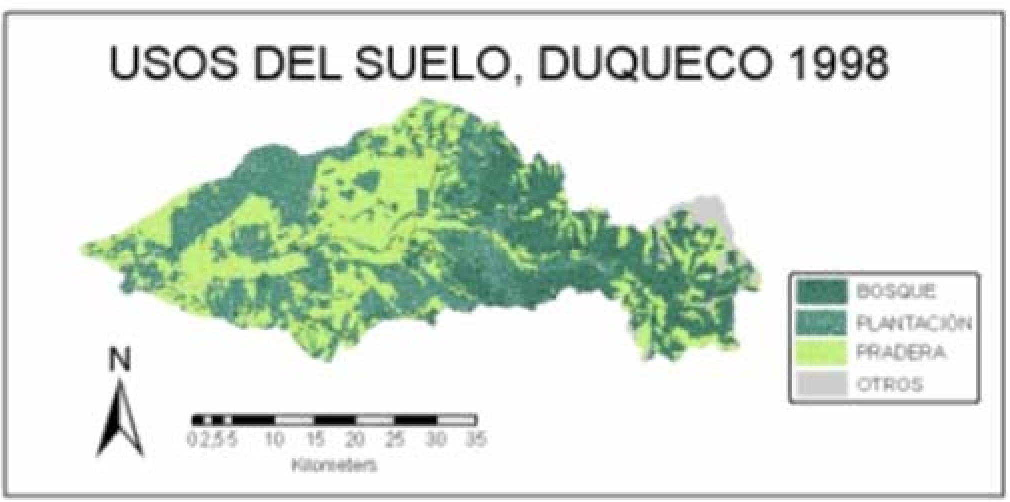


Figure 6. Land uses at Duqueco river basin.

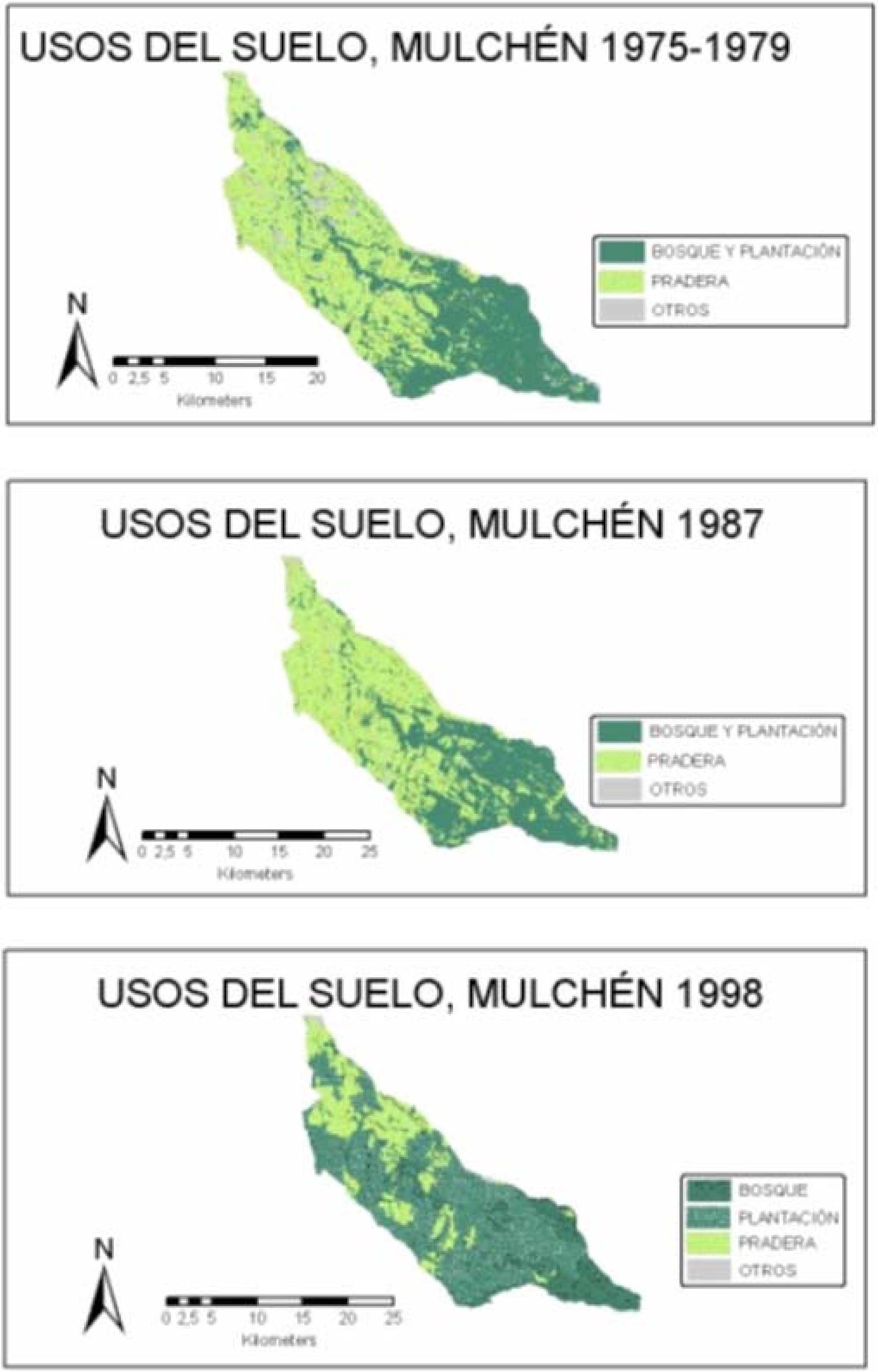


Figure 7. Land uses at Mulchén river basin.

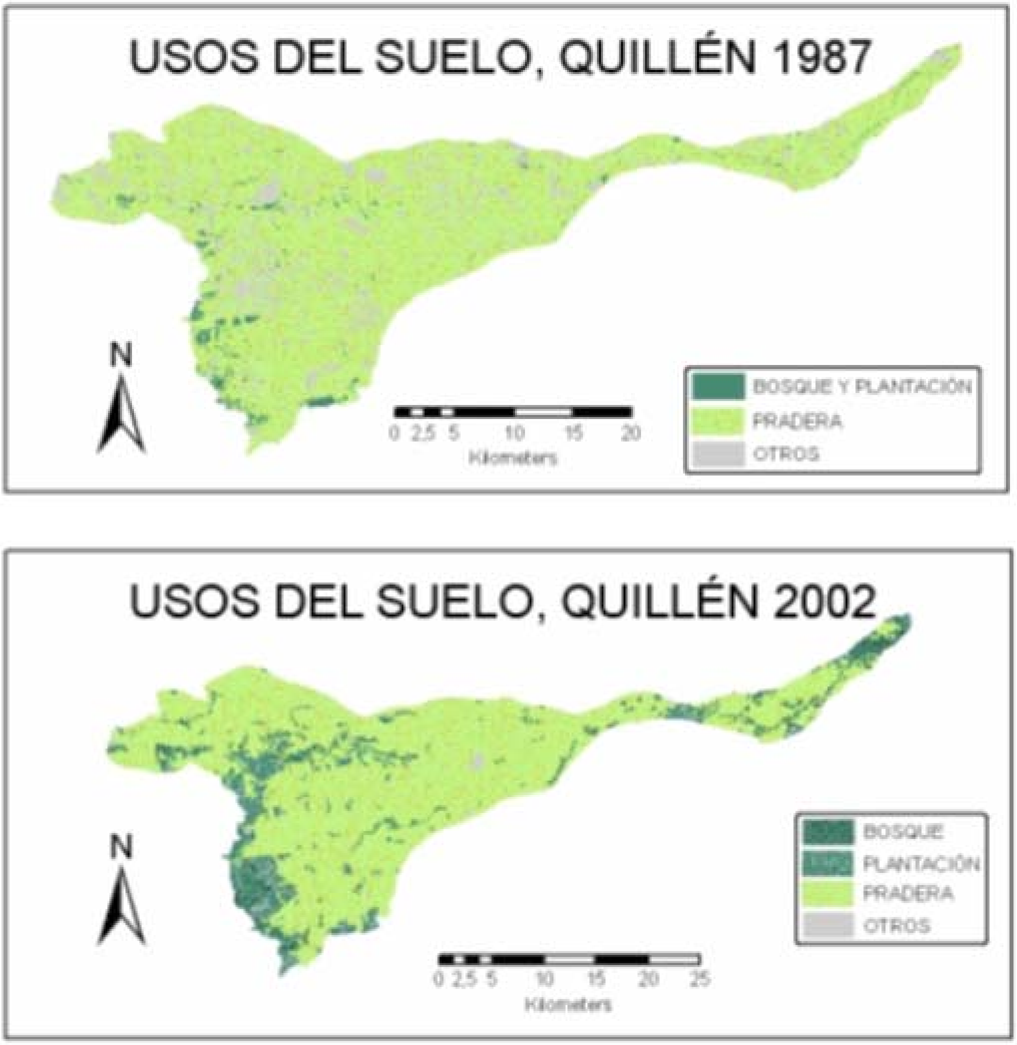


Figure 8. Land uses at Quillén river basin.

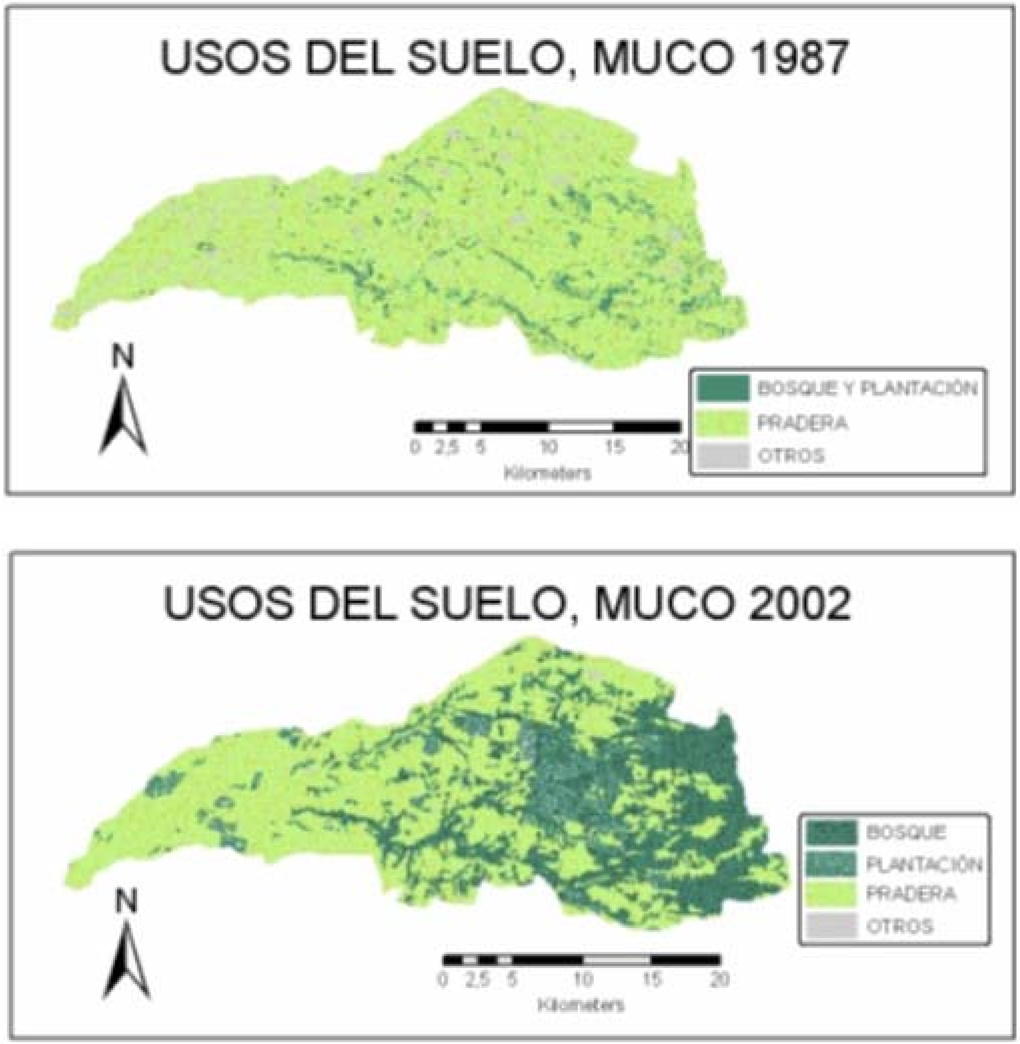


Figure 9. Land uses at Muco river basin.

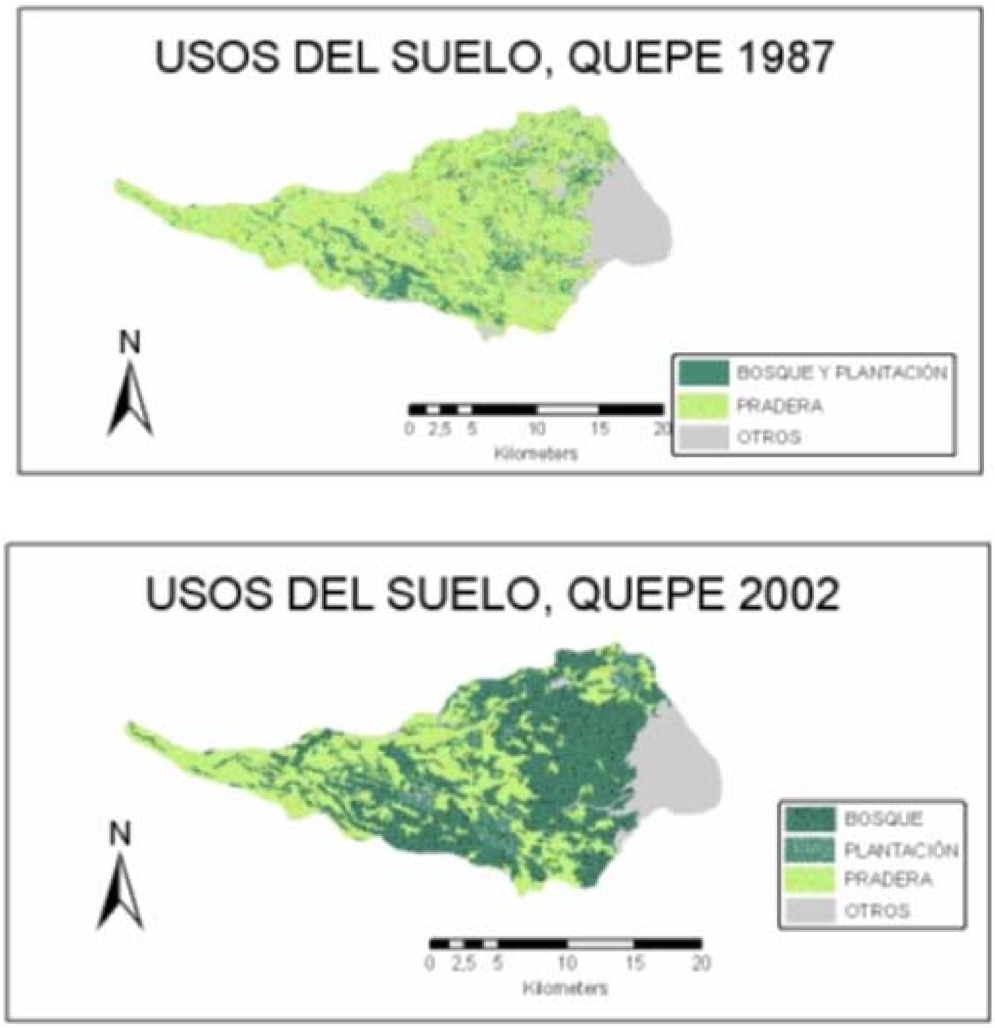


Figure 10. Land uses at Quepe river basin.

Table 4. Land uses evolution in specific large basins.

River basin	Land use types	Period for land use assessment			
		1975-1979	1987	1994	1998-2002
Caramávida	NF	40.31	69.21	56.14	56.14
	P			40.49	40.49
	A	33.44	30.44	3.38	3.38
	O	26.25	0.35	0.00	0.00
	Total	100.00	100.00	100.00	100.00
Duqueco	B	36.12	35.83	32.11	32.11
	P			32.13	32.13
	A	48.28	52.97	32.73	32.73
	O	15.59	11.20	3.03	3.03
	Total	100.00	100.00	100.00	100.00
Mulchén	B	41.79	42.31	23.53	23.53
	P			56.09	56.09
	A	51.79	56.29	19.82	19.82
	O	6.42	1.40	0.56	0.56
	Total	100.00	100.00	100.00	100.00
Quillén	B	-	3.24	6.95	7.35
	P			8.29	10.66
	A		84.24	84.40	81.18
	O		12.52	0.36	0.81
	Total		100.00	100.00	100.00
Muco	B	-	8.04	38.19	38.45
	P			6.08	8.12
	A		86.56	55.64	53.07
	O		5.40	0.09	0.36
	Total		100.00	100.00	100.00
Quepe	B	-	14.45	57.17	55.87
	P			3.91	6.33
	A		69.55	26.72	25.40
	O		16.00	12.20	12.39
	Total		100.00	100.00	100.00

3. DATA COLLECTION

3.1. Data collection and monitoring equipment in the experimental catchments

Data collection, monitoring periods and equipments from the operation of the different stations in the experimental catchment are summarized in Table 5.

Tabla 5. Records and data availability in the experimental catchments.

Catchment	Equipment	Data-Period	Period of data missing
Malalcahuello	Rain gauge 1	1997-2007	May2001-Nov2002
	Rain gauge 2	2004-2007	
	Limnigraph	1997-2007	
	Weather station	1999-2007	
	Rainfall interception plot 1 and 2	1998-2002	
Piedra Santa	Rain gauge	2004-2006	
	Limnigraph	2003-2006	
Aragón 1	Rain gauge	2004-2005	
	Limnigraph	2004-2005	
Aragón 2	Rain gauge	2004-2005	
	Limnigraph	2004-2005	
Los Pinos	Rain gauge 1	1997-2007	May2001-Dec2001
	Rain gauge 2	2006-2007	
	Rain gauge 3	2006-2007	
	Limnigraph 1	1997-2007	
	Limnigraph 2	2006-2007	
Pumillahue	Rain gauge	2005-2007	
	Limnigraph 1	2005-2007	
	Limnigraph 2	2006-2007	
	Rainfall interception plot	2005-2007	
Los Ulmos 1	Rain gauge 1	2000-2007	Mar2002-Aug2002
	Rain gauge 2	2006-2007	
	Limnigraph 1	2000-2007	
	Limnigraph 2	2006-2007	
Los Ulmos 2	Rain gauge 1	2000-2007	Mar2002-Aug2002
	Rain gauge 2	2006-2007	
	Limnigraph 1	2000-2007	
	Limnigraph 2	2006-2007	
La Reina	Rain gauge	2005-2007	-
	Limnigraph 1	1997-2007	Nov2003-Jun2005
	Limnigraph 2	2006-2007	-
	Weather station	1997-2007	No precipitation data from Jan2004-Jul2005

3.2. Discharge data in the large river basins

The information of discharge in the large river basins has been obtained from the data bases of the Dirección General de Aguas (the Chilean Water Authority), according to the detail of Table 6.

Table 6. Available discharge data from large river basins.

River		Discharge gauging station				
		Name of location	Controlled catchment area (km^2)	Geographic coordinates (UTM)		Period of discharge records
Number[a]	Name			W	S	
01	Duqueco	Villucura	1545	72º12"	37º33"	1963-2004
02	Caramávida	Caramávida	94	73º29"	37º36"	1960-1991
03	Bureo	Mulchén	567	72º14"	37º43"	1960-2004
04	Mulchén	Mulchén	434	72º14"	37º43"	1960-2004
05	Butamalal	Butamalal	118	73º15"	37º49"	1960-1996
06	Purén	Tranamán	354	73º01"	38º02"	1960-2004
07	Traiguén	Victoria	106	72º19"	38º13"	1960-2004
08	Quino	Longitudinal	344	72º22"	38º18"	1960-2003
09	Quillén	Galvarino	734	72º47"	38º24"	1960-2004
10	Muco	Puente Muco	650	72º25"	38º37"	1960-2004
11	Quepe	Vilcún	386	72º13"	38º41"	1961-2004
12	Puyehue	Quitratúe	138	72º40"	39º09"	1948-2004
13	Cruces	Rucaco	1740	72º54"	39º33"	1969-2004
14	Iñaque	Máfil	424	72º57"	39º40"	1986-2004
15	Collilelfu	Los Lagos	581	72º49"	39º51"	1987-2004
16	Santo Domingo	Rincón de la Piedra	127	73º08"	39º23"	1992-2004
17	Damas	Tacamó	408	73º03"	40º37"	1986-2004
18	Negro	Chahuilco	2318	73º14"	40º42"	1986-2004

[a] Numbers refer to Figure 2.

The fluviometric stations in these river basins correspond to natural sections of the channels partially improved in some cases. The analyzed records are at daily level, because only from mid 1990`s a change from limnimetric records (with reading once to the day) to continuous records with digital data loggers began.

3.3. Precipitation data in the study zone

The information of precipitation in the study zone is obtained from records of 230 stations operated by the Dirección General de Aguas and the Dirección Meteorológica de Chile. Sixty six per cent of these stations have daily records while the rest has monthly data, covering different time periods. The location of these stations is in Figure 11.

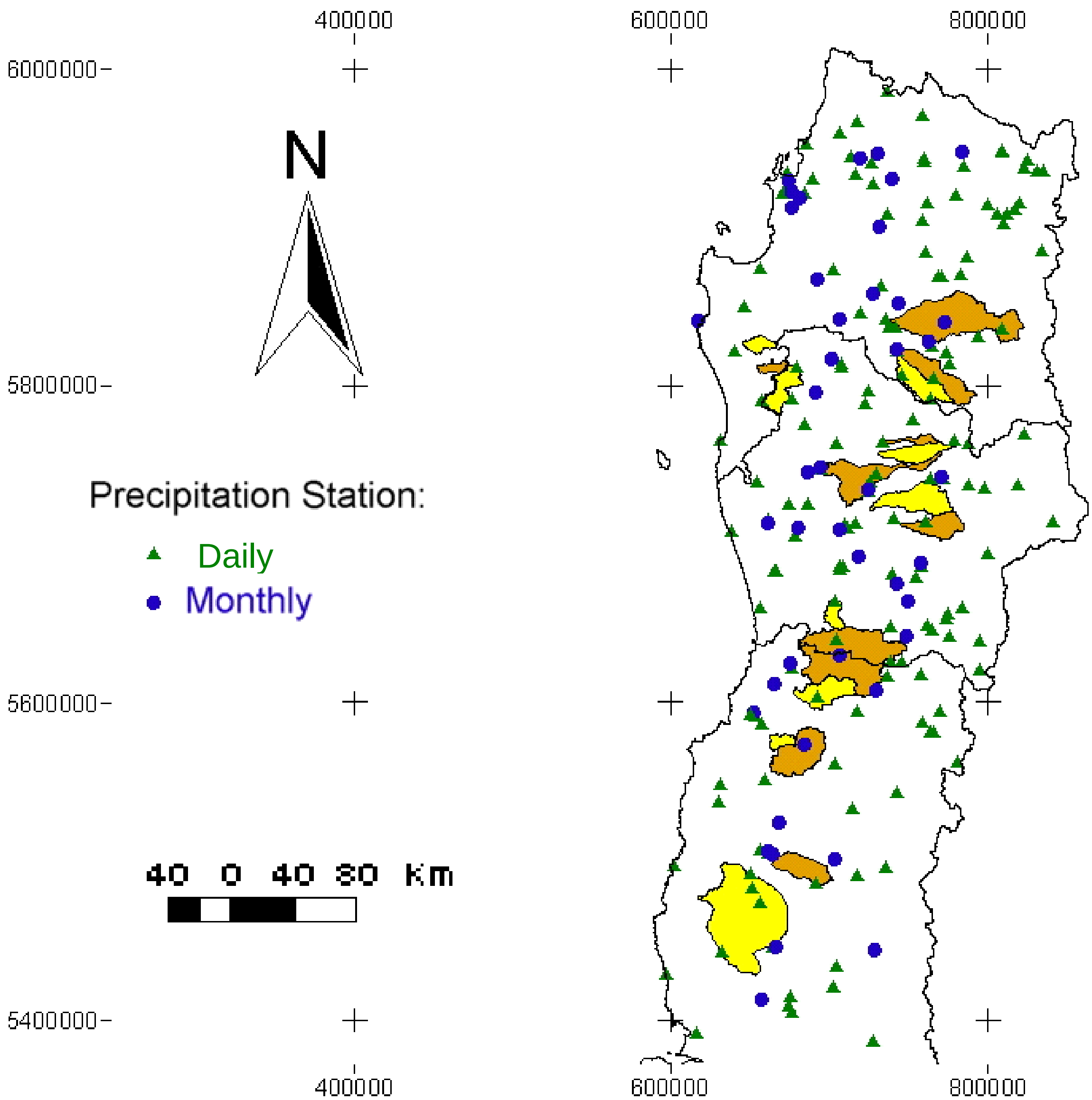


Figure 11. Location of precipitation stations in the study zone.

4. RESULTS

4.1. Land use changes and water production in experimental catchments

4.1.1 Annual runoff for different forest cover conditions

Runoffs at La Reina catchment were studied during pre-harvesting (years 1997, 1998 and 1999) and post-harvesting (years 2000 to 2006) periods. Also, runoffs registered in the Los Ulmos 1 and 2 and La Reina catchments were compared for the period between years 2000 and 2002.

At the La Reina experimental catchment, annual runoff ranged between 321 and 1653 mm during the pre-harvesting period (years 1997, 1998 and 1999) and between 1773 and 2427 mm in the first three years of the post-harvesting period (years 2000, 2001 and 2002), Iroumé *et al*. (2005). Mean annual runoff coefficients (annual runoff/annual rainfall) were 40.1% during pre-harvesting conditions (range 20.5-51.6%) and 69.9% in the post-harvesting period (range 69.1-71.6%). Annual runoffs were on average 917 and 2033 mm/year during pre- and post-harvesting periods respectively, resulting in a mean increase of 1116 mm/year (i.e. 122%) after the clearcut of the *Pinus radiata* plantation that covered the 79.4% of the catchment area. The 122% increase in runoff may be partly due to the higher rainfall during the post-harvesting period (on average the annual rainfall was 621 mm/year or 27% higher than in the pre-harvesting period). The actual importance of timber harvesting is not easy to determine, although a reduction in interception and transpiration rates certainly occurred after logging. The effect of forest removal on runoff was analyzed using a double mass approach comparing data from La Reina and Los Pinos catchments, Figure 12.

The significant increase in gradient (from 0.73 to 1.42) of the graph of the first three years of the post-harvesting period (years 2000 to 2002) compared with the pre-harvesting period indicates that more water was discharged from the catchment when the vegetation cover was removed. The increase in runoff commenced at the beginning of February 2000 which coincided with the final period of harvesting operations initiated in October 1999 (Iroumé *et al.*, 2005). Projecting the 1997-1999 cumulated runoff trend beyond January 2000, it is possible to estimate "virtual" annual runoff for years 2000, 2001 and 2002 as 802, 1088 and 1175 mm, respectively. Comparing these estimations with the measured annual runoffs for the same years (1773, 1898 and 2427 mm), the double mass analysis indicates a mean increase of 1013 mm/year (971, 810 and 1258 mm in years 2000, 2001 and 2002, respectively).

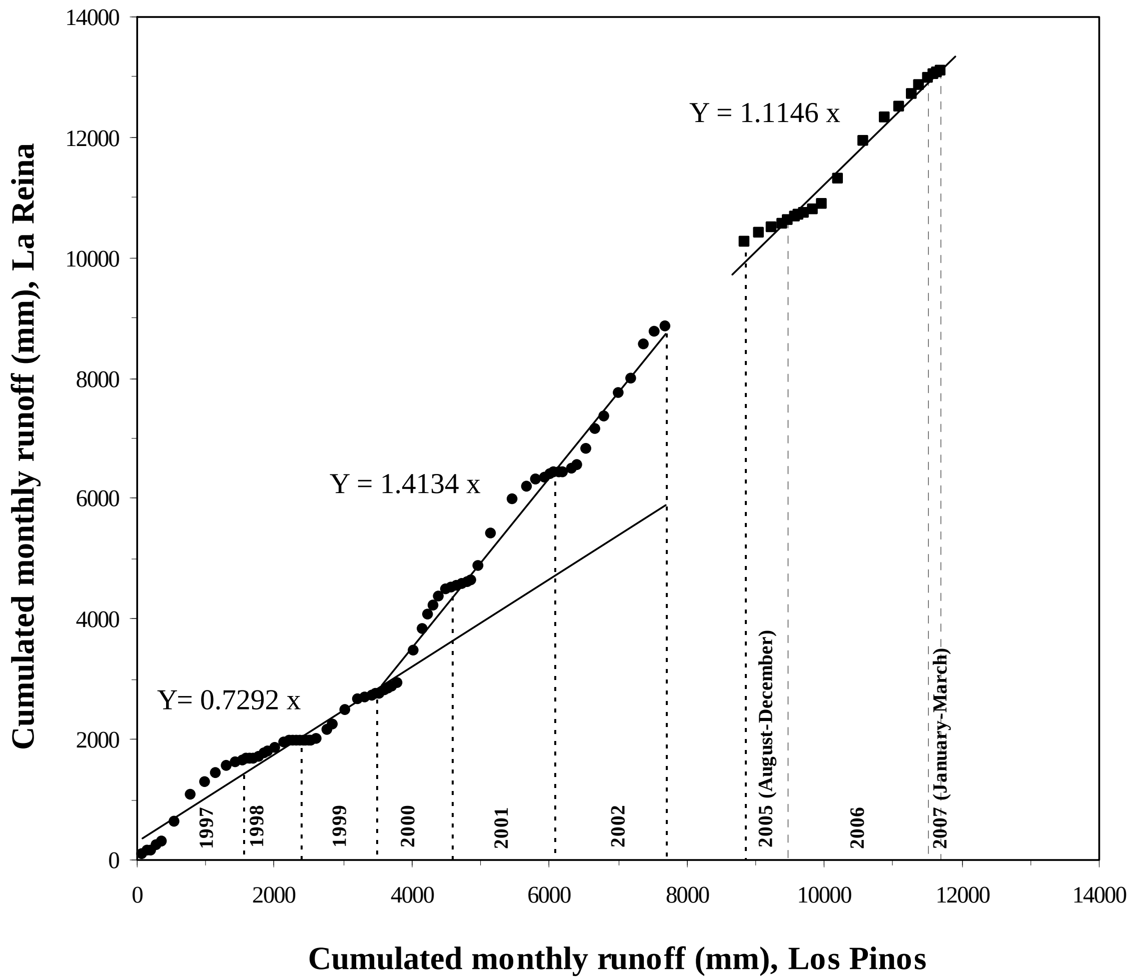


Figure 12. Monthly runoff double mass curve analysis between Los Pinos and La Reina catchments for the 1997-2002 study period (from Iroumé *et al.*, 2005).

As previously mentioned mean annual runoff was 917 mm/year for the pre-harvesting period (years 1997, 1998 and 1999). After timber harvesting, runoff increased on average 1116 mm/year between years 2000 and 2002, but from the double mass analysis a smaller amount (1013 mm/year) could be attributed to the effect of forest removal, with the remaining 103 mm/year probably caused by the higher rainfall occurred during the post-harvesting period. Therefore, in average a 110% increase in runoff during the post-harvesting period can be associated with clearcutting the *Pinus radiata* plantation that covered the 79.4% of the catchment. For this location and level of annual rainfalls between 2000 and 2002, interception losses of 460 mm/year and transpiration of 570 mm/year have been measured in a 20-22 years old *Radiata pine* plantation (Huber and López, 1993; Huber and

Iroumé, 2001). The 1013 mm/year mean increase in runoff after timber harvesting derived from the double mass analysis seems consistent with the elimination of the interception capacity and the reduction in transpiration potential of the remaining vegetation as compared with the previous forest cover.

By expanding the double mass approach to compare runoff from La Reina and Los Pinos catchments between August 2005 and March 2007 (see Figure 12), it is possible to appreciate that the effect of forest removal on runoff is still noticeable. But in this case the gradient of the graph of the 2005 (August)-2007 (March) post-harvesting period has fallen to 1.11 indicating that after 6 years of development of the new forest water production has initiated a recovery towards pre-harvesting levels.

Annual evapotranspiration rates measured in the La Reina catchment during the period 1997-2006 (annual evapotranspiration as ET= P – Q, being P and Q annual measured precipitation and runoff) are compared with ET estimated using the Zhang's model (Zhang *et al*., 2001). Zhang's model estimates annual ET in fully forested or grassed catchments from annual precipitation in the area. The result of this comparison is presented in Figure 13.

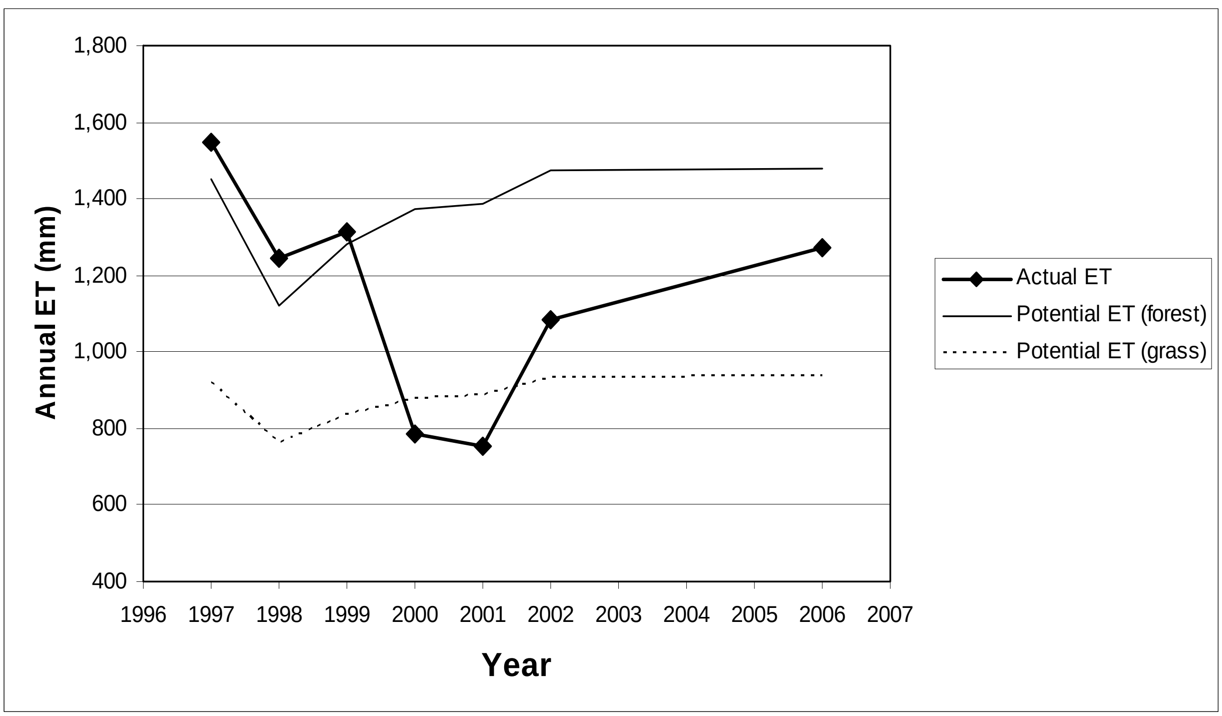


Figure 13. Actual ET (ET = P-Q) and Potential ET (for forest and grass conditions, Zhang model) for the La Reina conditions.

Actual ET in La Reina for years 1997 to 1999 (La Reina fully forested) are comparable but even higher than the ET estimates for a forested watershed using Zhang's model. Years 2000 and 2001 are the first two years after forest clearcutting, and actual ET is even lower then estimated ET from a fully grassed catchment. Six years after the plantation, the new *Eucalyptus* forest has a lower ET rate than a fully developed plantation of Monterey pine like the one covering La Reina in years 1997 to 1999, Figure 13.

Runoffs registered in Los Ulmos1 and 2 and La Reina were compared for the period 2000-2002. For the three years of the study period, annual runoffs in Los Ulmos1 (forest planted in 1997, 81% of the area) were lower than at the Los Ulmos2 catchment (forest planted in 2000, 68% of the area), Iroumé et *al*. (2005). In 2000 and 2001 the differences in runoff between Los Ulmos1 and Los Ulmos2 were 59 and 50 mm/year, but in 2002 the difference augmented to 217 mm/year, reflecting the higher water consumption of the *Eucalyptus* plantation in its fifth year of growth. In 2002 the plantation at Los Ulmos1 should have intercepted between 320 and 470 mm/year and the vegetation at Los Ulmos2 no more than 100 to 150 mm/year (Huber and López, 1993; Huber and Iroumé, 2001). The difference in interception losses between these two catchments (220-320 mm/year) may explain the difference in runoff. Runoff differences between Los Ulmos1 and Los Ulmos2 should reach a maximum in years 2004 or 2005, and then decrease as the plantation in Los Ulmos2 develops and becomes similar (in terms of interception and transpiration capacities) to the one in Los Ulmos1. From 2000 to 2002 La Reina and Los Ulmos2 catchments featured a relatively similar vegetation cover. During these years, runoff coefficients ranged between 69.1% and 71.6% in La Reina and 60.3% and 64% in Los Ulmos2. A larger size (La Reina = 34.4 ha and Los Ulmos2 = 16.1 ha), higher percentage of clearcut area (79.4% in La Reina and 68% in Los Ulmos2) and steeper terrain (mean slope of 23.7% in La Reina against 20.6% in Los Ulmos2) may explain the differences in annual runoff coefficients.

Data of annual precipitation and runoff registered from 1997 to 2006 at La Reina, Los Ulmos1 and Los Ulmos2 was used to generate a relationship between annual runoff coefficient and the degree of development of the plantation. The relationship (r^2 of 0.70) between annual runoff (in percentage of annual rainfall) and the number of years after the establishment of the plantation shows a decreasing trend from about 68% the year after timber harvesting to 36% after 22 years of plantation growth, Figure 14. The data used for the analysis come from years with different annual total rainfall, but clearly show a decrease in the annual runoff coefficient as the plantations develop and increase their water consumption capacities (i.e. interception and transpiration rates).

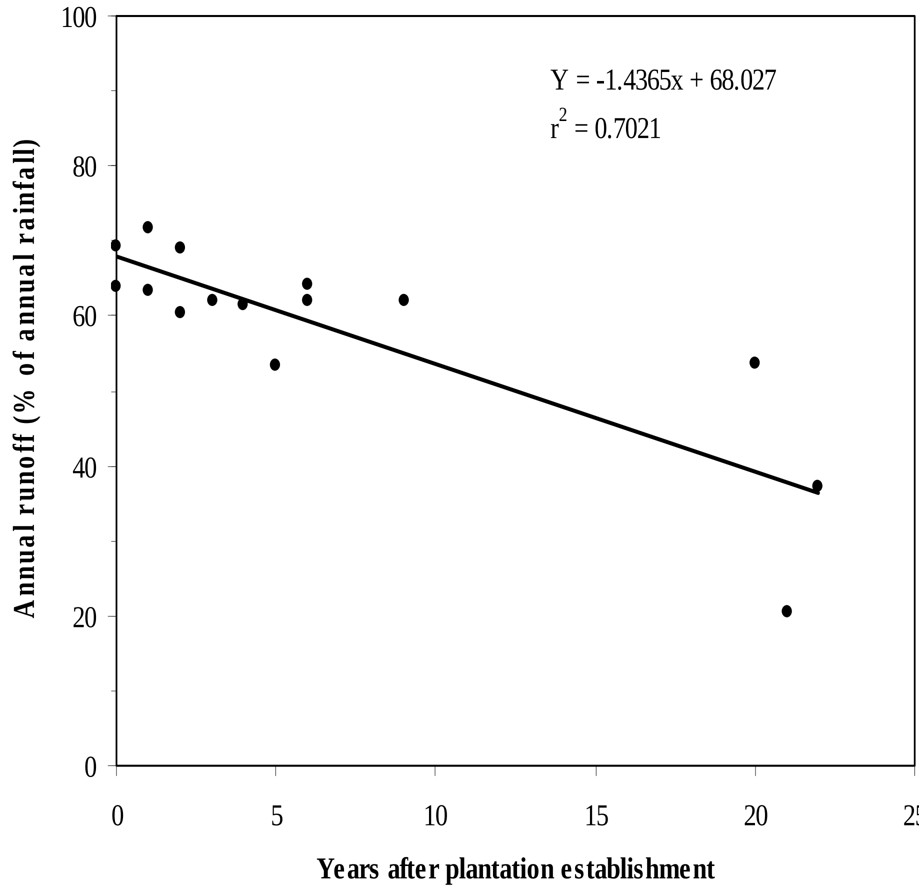


Figure 14. Annual runoff depletion associated with plantation growth (from Iroumé *et al*., 2005, plus additional data)

4.1.2 Summer runoff for different forest cover conditions

Summer runoffs at La Reina catchment were studied for periods under pre-harvesting and post-harvesting conditions. Also, runoffs registered in the Los Pinos, Los Ulmos1 and 2 and La Reina catchments were compared for different summer periods (Iroumé *et al.* 2005).

Runoffs in the four catchments for one of the summer study periods (December 2000 to March 2001), expressed as daily mean specific discharge (l/s/ha) are presented in Figure 15.

.

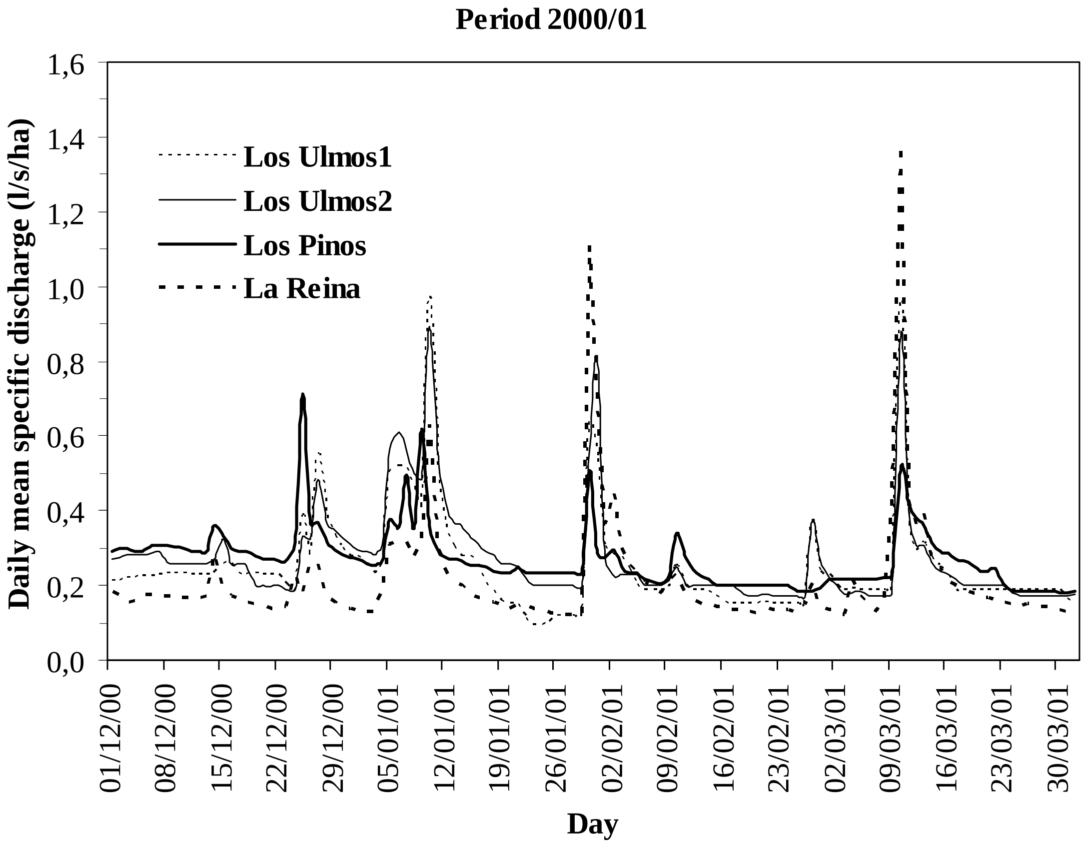


Figure 15. Daily mean specific discharge for period 1st December 2000 to 31st March 2001 in the four catchments (from Iroumé *et al.* 2005).

It is possible to appreciate that the Los Pinos catchment has higher baseflows (represented by the flows between storm periods). Its bigger storage capacity derived from larger size and deeper soils compared with that of the other catchments, increases soil water reserves which maintain baseflows in the dryer summer periods. The two Los Ulmos catchments behave similarly, but Los Ulmos1 shows a lower baseflow than Los Ulmos2. The differences seem to reflect the higher water consumption by the established plantation in the first one, while in second the vegetation has been reduced to the riparian areas and some bushes and residues from the previous harvesting operations.

The effect of forest removal in summer water production is analysed using a double mass approach comparing data from La Reina with Los Pinos as the control. Figure 16 shows the relationship between accumulated daily runoff in La Reina and Los Pinos for several summer periods (summer period is assumed from 1st December one year to 31st March following year).

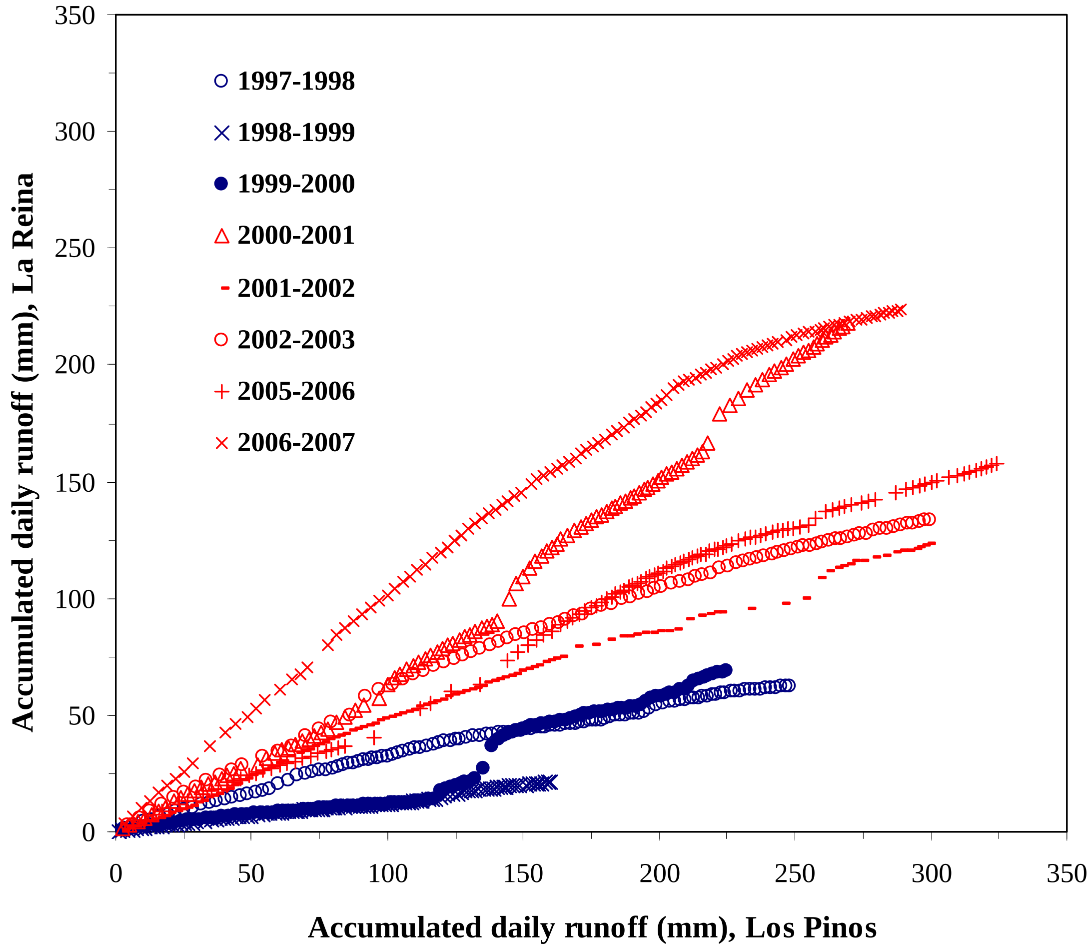


Figure 16. Runoff double mass curve analysis between Los Pinos and La Reina catchments for different summer periods (in blue, pre-harvesting conditions; in red, post-harvesting conditions)

A noticeable change in the slope of the accumulated runoff occur since the 2000-2001 plot, indicating an important increase in runoff at the La Reina catchment compared with the two pre-harvesting periods (1997-1998 and 1998-1999). The accumulated daily runoff plot in the first half of the 2000-2001 period follows the same trend than in 1998-1999 (a pre-harvesting period), but an important increase in runoff at La Reina can then be appreciated (the change in the accumulated runoff relationship occurs since the beginning of February 2000, what is consistent with the clearcutting operation initiated in October 1999 but concentrating its major effects at the end of the harvesting period). In the last two months of the 1999-2000 period, the plantation at La Reina was in the final steps of the clearcutting and forest removal operations, and in 2000-2001 La Reina was in a post-harvesting condition. The increase in runoff registered in periods 1999-2000 (especially in the last two months of this summer period) and the following clearly indicates the effect of timber harvesting in this catchment.

4.2. Land use changes and water production in large river basins

4.2.1 Precipitation pattern in the study zone

Impacts of land use change in flow production are presented for the Duqueco, Caramávida, Mulchén, Quillén, Quepe and Muco large river basins (basins number 1, 2, 4, 9, 10 and 11 in Figure 2). Precipitation pattern from the area where these six river basins concentrate has been characterized using rainfall data from the period 1963-2004 registered in the pluviometric stations of Los Ángeles, Collipulli, Cañete, Trupán, Laguna Malleco and Temuco (Maquehue). The location of these six river basins and six pluviometric stations is shown in Figure 17.

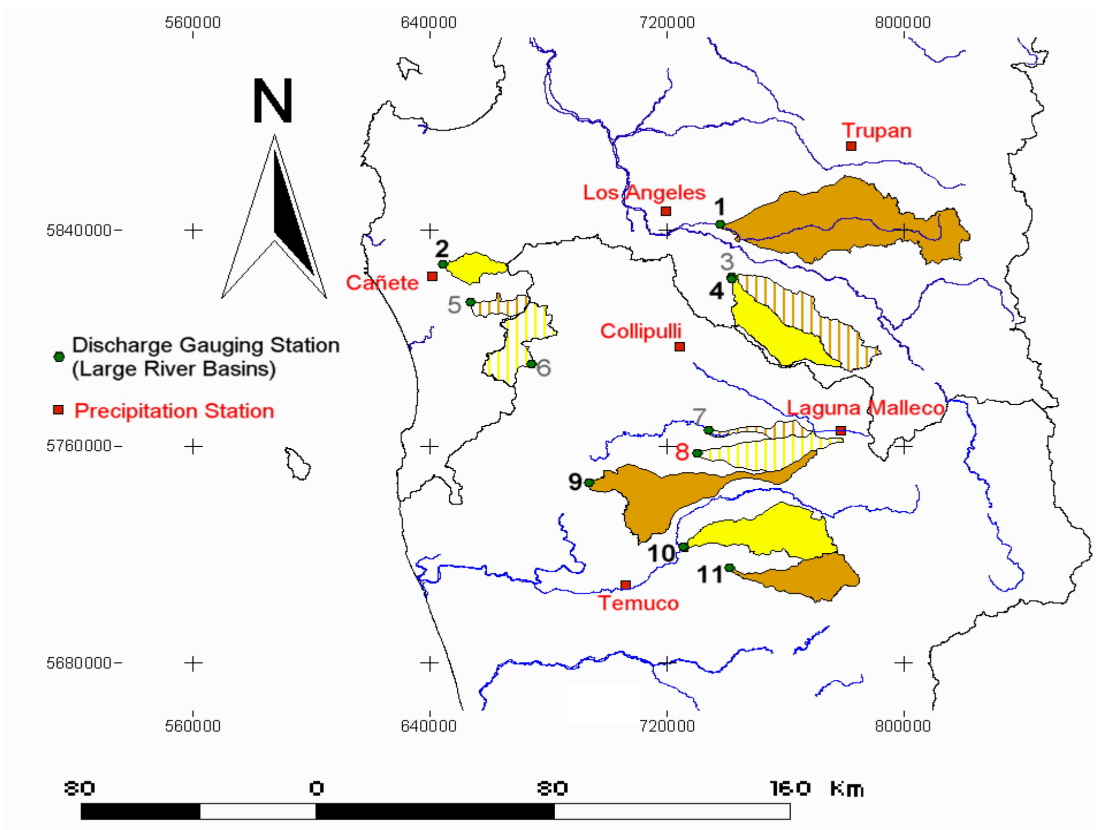


Figure 17. Location of selected river basins and pluviometic stations.

Figure 18 presents annual rainfalls during the period 1963-2004 registered in the pluviometric stations of Los Ángeles, Collipulli, Cañete, Trupán, Laguna Malleco and Temuco (Maquehue), which have been used to characterize the precipitation pattern of the study zone. It is observed that the annual precipitation of all the stations has a similar behavior throughout the years of the study period. For example, the rainiest and the driest years are the same in all the stations. An increase of annual precipitations from west to east is noticeable, with the smaller values in the Los Angeles station located in the central valley, and the higher in the Laguna Malleco station at the foothills of the Andes Mountain range.

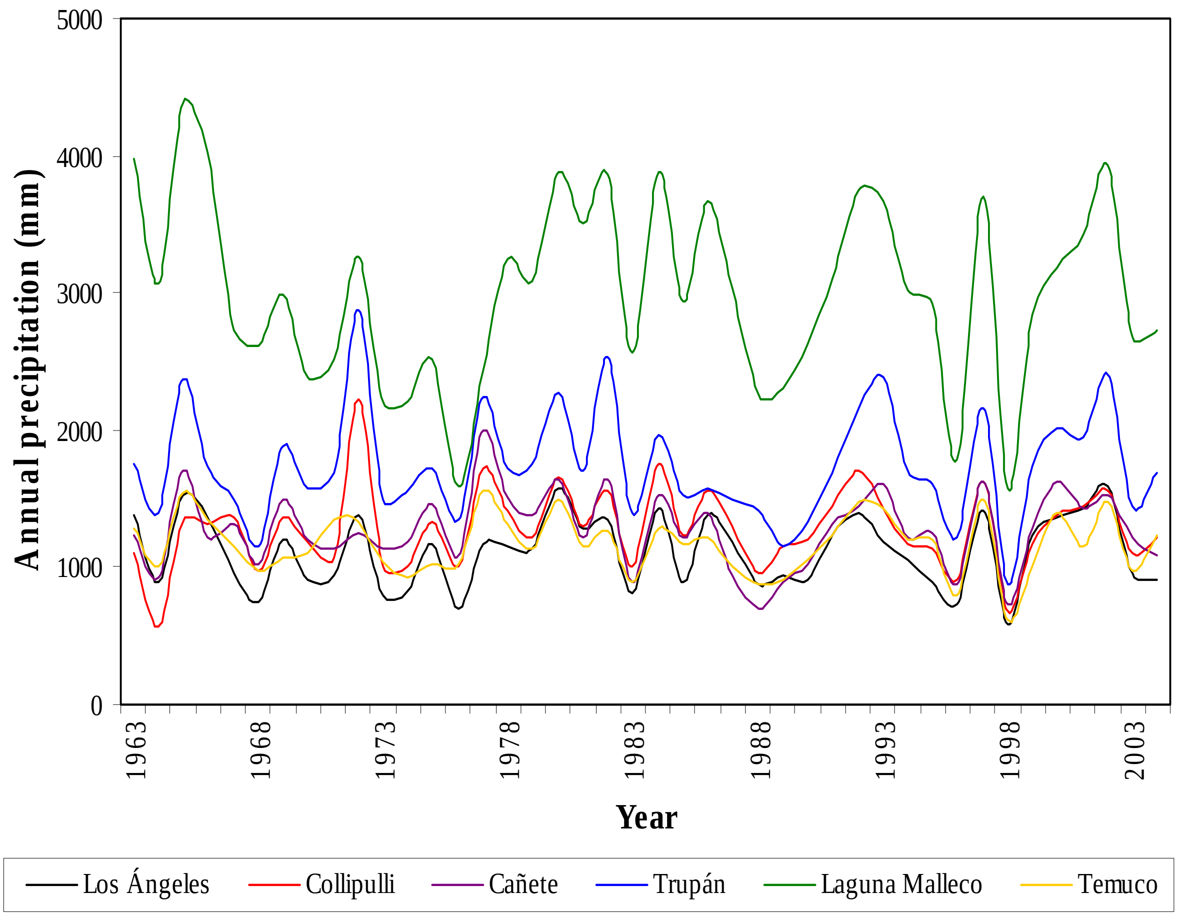


Figure 18. Annual rainfall regimes at the Los Ángeles, Collipulli, Cañete, Trupán, Laguna Malleco and Temuco (Maquehue) stations during period 1963-2004.

When analyzing the 20-year moving means of these stations (Figure 19), the condition of similar behavior is reinforced. The records of all these stations follow a similar trend, situation that allows considering their pluviometric data to characterize the precipitation of the study zone and to use their precipitation as ***Control*** to analyze the tendency of the water production of the river basins included in this study.

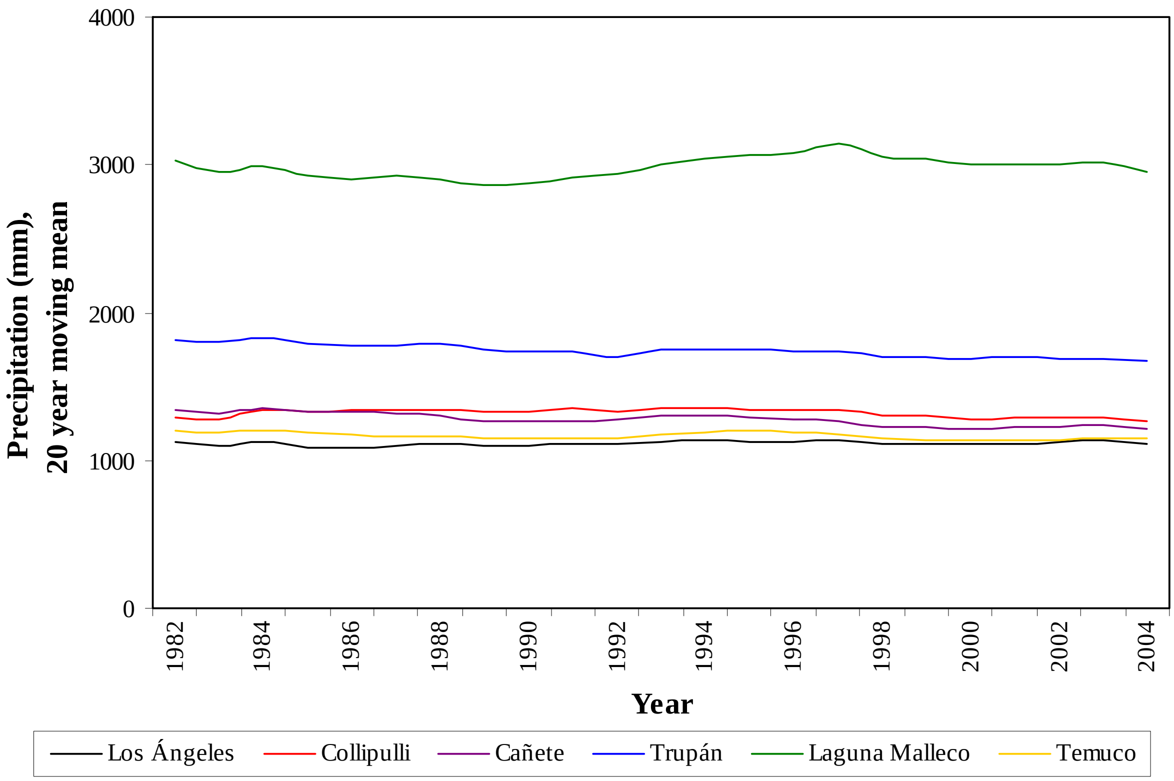


Figura 19. Annual precipitation 20-year moving means at the Los Ángeles, Collipulli, Cañete, Trupán, Laguna Malleco and Temuco (Maquehue) weather stations, period 1963-2004.

The homogenous behavior of the precipitation records of these stations allows defining as ***Control station*** the arithmetic mean of annual precipitation registered in these pluviometric stations.

4.2.2 Inter-annual runoff behaviour in the study basins

The results of the comparison among cumulative annual runoff of Quepe, Muco and Quillén and cumulative annual precipitation at Control station are presented in Figure 20.

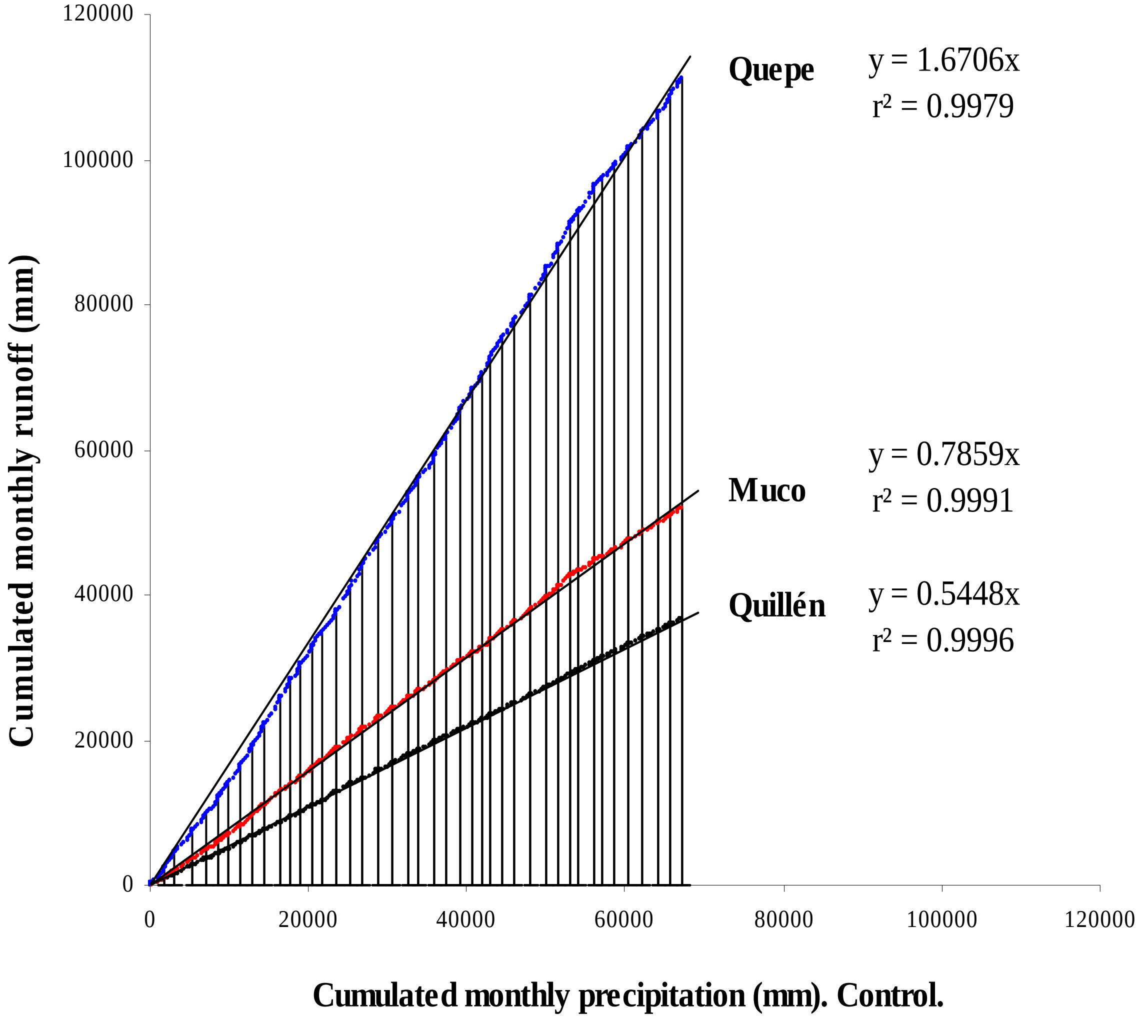


Figure 20. Comparison among cumulative annual runoff of Quepe, Muco and Quillén and cumulative annual precipitation at Control station.

As it can be seen in Figure 20, is not possible to appreciate changes in the homogeneity of the accumulated annual runoff trends in the Quepe, Muco and Quillén river basins (r^2 are higher than 0.99 in the three equations of best fit). Between years 1987 and 2002, the area covered with forests (plantations and native forests) changed from the 14 to 6% in the Quepe river basin, stayed in 8% for Muco and increased from 3 to 7% in Quillén, maintaining these three river basins a mainly agricultural-cattle raising vocation. Land use changes in the river basins Quepe, Muco and Quillén have not been important, and would explain the homogeneity in annual runoff trends. Anyway, the changes in forested area are below the 20% of total basin area, threshold that has been mentioned by

Keenan *et al*. (2004) as to be able to generate changes in water production produced by an increase/decrease of the forested surface.

Since the cumulated annual runoffs of these river basins are homogenous, the arithmetic mean of the annual run-offs in the fluviométricas stations Quepe, Muco and Quillen will be used as ***Control Station*** to analyze the tendency of the water production of the other river basins considered in this study.

The comparison between the cumulated annual runoffs of the Caramavida river basin water gauging station and ***Control station*** is shown in Figure 21. It is possible to appreciate a break in the homogeneity of the cumulated annual runoffs from year 1979, as of which the slope of the tendency of the cumulated values decreases from 1.32 in period 1960-1978 to 1.1 in period 1979-1991. This means that from year 1979 a decrease of annual runoff in Caramávida river basin has taken place. In this river basin, towards years 1975-1979 near 40% of the total area was covered by forests, while in 1994 forests covered near the 97% of the basin surface. This fact indicates that this river basin has undergone a significant land use change since de last years of the 1970`s.

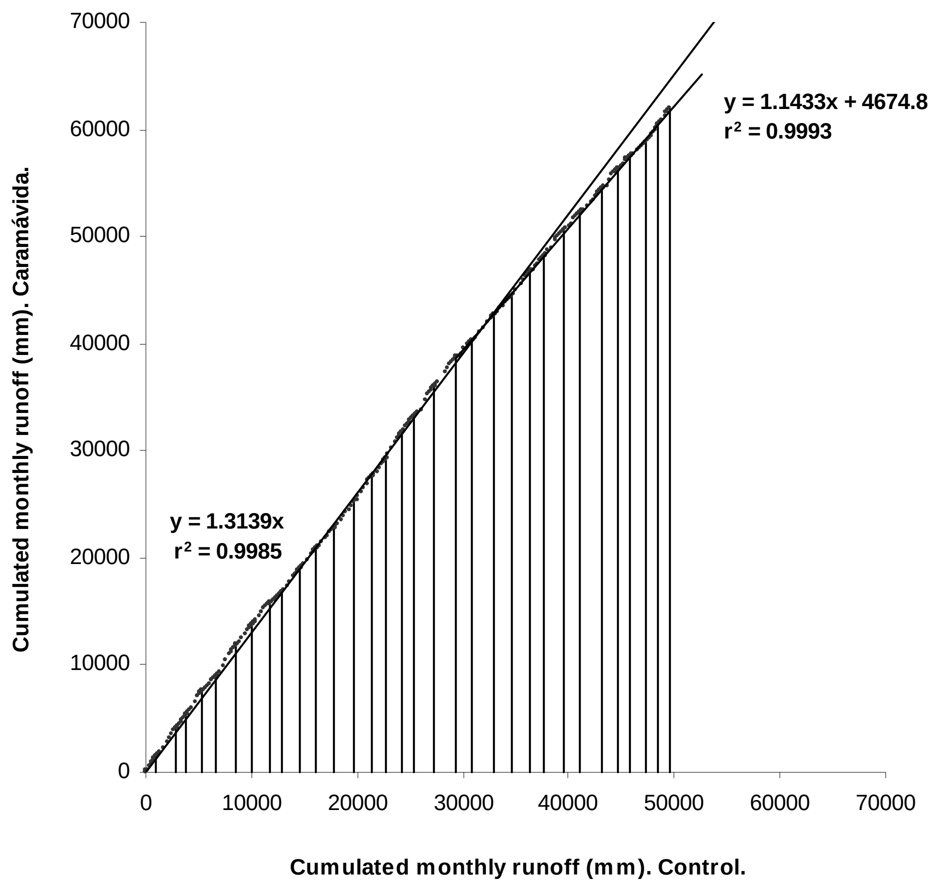


Figure 21. Comparison among cumulative annual runoff in Caramávida and cumulative annual runoff of *Control station*.

The comparisons between the accumulated annual runoffs of the Duqueco and Mulchén river basins with those from the *Control station* are shown in Figure 22.

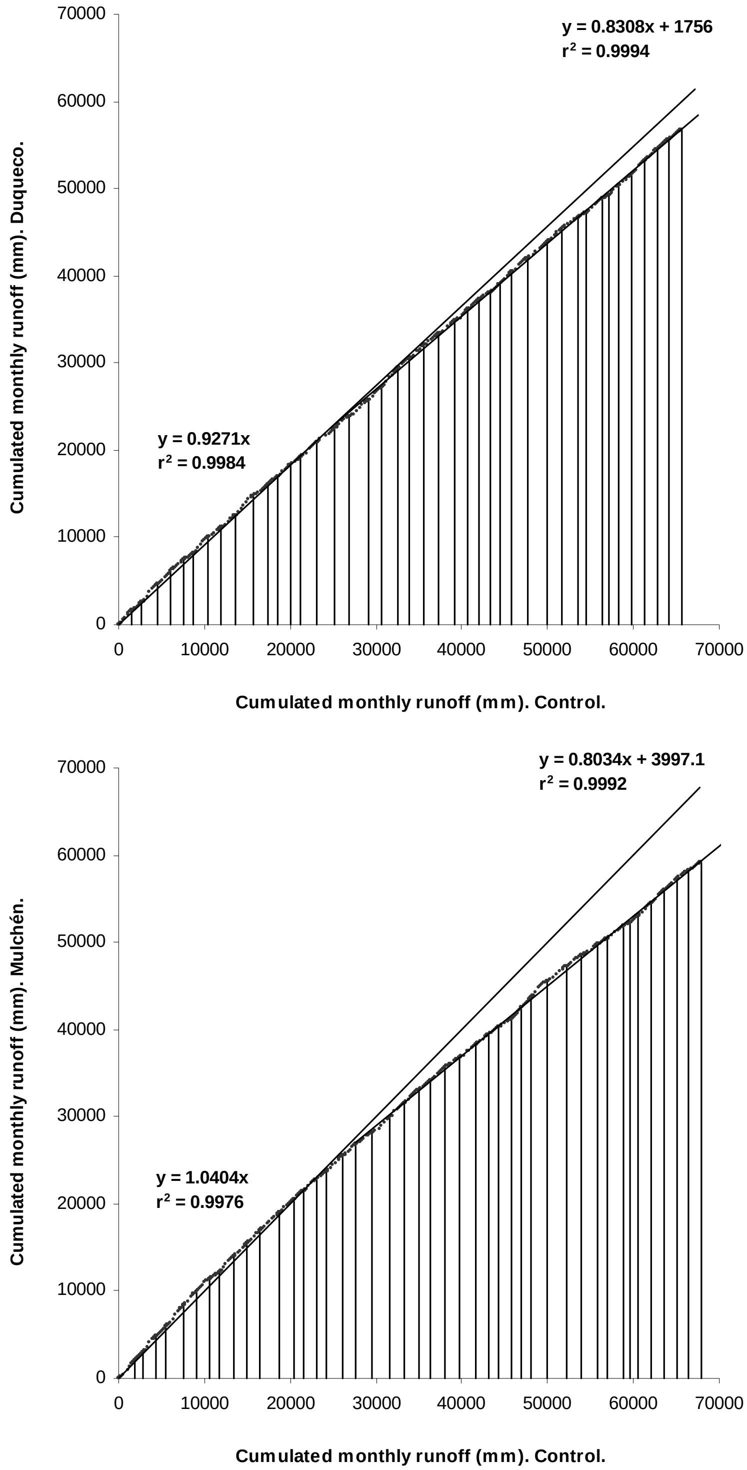


Figura 22. Comparison among cumulative annual runoff in Duqueco (above) and Mulchén (below) river basins and cumulative annual runoff at *Control station*.

In these two cases it is also possible to appreciate a break in the homogeneity of the accumulated annual runoff trends, and in both river basins it happens in year 1979. For the Duqueco river basin, since 1979 the slope of the tendency of the accumulated values changes from 0.93 for the period 1963-1978 to 0.83 in period 1979-2004, whereas in the case of the Mulchén river basin this slope is reduced from 1.04 in period 1961-1978 to 0.80 in period 1979-2004. This means that since year 1979, in Duqueco and Mulchén a decrease of annual water production has taken place.

In Duqueco, during 1975-1979 the forested area was the 36% of the total basin surface but in year 1994 the area under forests was 64% of total area. In the case of Mulchén, the area under forest increased from 42 to 80% of total basin area since 1975-79 to 1994.

In the Caramávida, Duqueco and Mulchén river basins the increase of the forested area was sustained in new plantations that represented a significant land use change. Agreeing with the results of 137 experimental river basins studied by Andrássian (2004), with the studies of Smith and Scott (1992) and Kennan *et al.* (2004) in river basins in Australia and by Dye (1996) in South Africa, among others, the decrease of annual runoffs registered since 1979 in the Caramávida, Duqueco and Mulchén river basins could be attributed to the increase in the area under forests.

The reductions in runoff noticed since 1979 in the Caramávida, Duqueco and Mulchén river basins (total and mean annual reduction for the period starting in year 1979) are summarized in Table 7.

Table 7. Reduction in runoff in the Caramávida, Duqueco and Mulchén river basins.

River basin	Study period	Runoff reduction			
		Year of the break in the accumulative runoff trend	Period of runoff reduction	Total runoff reduction in the period in relation with the previous period (mm)	Annual runoff reduction (mm/year)
Caramávida	1960-1991	1979	1979-1991	3195	246
Duqueco	1963-2004	1979	1979-2004	4078	157
Mulchén	1961-2004	1979	1979-2004	11442	440

The decrease in water production since 1979 in these three river basins can be associated to the increase in evapotranspiration capacity of the new forests. The increase in evapotranspiration losses due to the increase of the afforested area (in percentage of the total area) in these three river basins is determined using the model proposed by Zhang *et al.* (2001), Table 8.

Table 8. Increase in evapotranspiration losses in Caramávida, Duqueco and Mulchén associated to increases in forests area (in percentage of total basin area), for each river basin.

		River basin		
		Caramávida	Duqueco	Mulchén
Forested area (% of total basin area)	1975-1979	40	36	42
	1994	97	64	80
Increase of forested area (%of total basin area) between periods		57	28	38
Increase in evapotranspiración losses estimated using the Zhang model (Zhang *et al*., 2001), in mm/year	Considering the minimum precipitation	143	71	96
	Considering the maximum precipitation	296	148	199
	Considering the mean precipitation	210	105	141
Runoff reduction, in mm/year		246	157	440

In this table, the annual average precipitation in the pluviometric station of Los Angeles has been defined as “minimum precipitation” (1138 mm in period 1967 to 2004) which registers the lower annual precipitations between the stations used to characterize the precipitation pattern, as “maximum precipitation” the mean annual precipitation for the same period in the Laguna Malleco station that presents the higher precipitations between the considered stations (3039 mm for period 1967 to 2004), and as “average precipitation” the arithmetic mean of the mean annual precipitations in the six stations (1634 mm, period 1967-2004).

In the Caramávida and Duqueco river basin, the reductions in water production in 246 and 157 mm/year, respectively, are of the same order of magnitude than the estimated increases in evapotranspiration rates due to the increase in the areas under forest. Higher evapotranspirations of 246 and 157 mm/year are estimated Caramávida and Duqueco, which tends to confirm that the decrease in runoff from 1979 in these two river basins could be controlled by the increase in the forested area. For the Mulchén river basin, the reduction in runoff is of the order of 440 mm/year while the increases in evapotranspiration are estimated in the range of 96 to 199 mm/year, reason why the diminution in the runoffs could not be attributed only to the increase of the plantations, and other water uses such as irrigation or drinking water supply could be contributing.

4.2.3 Flow duration curves in the study basins

The study of the changes occurred in water production of the Caramávida, Duqeco and Mulchén river basins is complemented by means of the analysis of the mean daily discharge flow duration curves. Figure 23 presents the mean daily discharge flow duration curves of the Caramávida river basin, corresponding to the records of all the period of availability of data, to the 1960-1978 period considered as previous to the plantation development and the 1979-1991 period immediately after the break in the water production trend that shows preceding Figure 21.

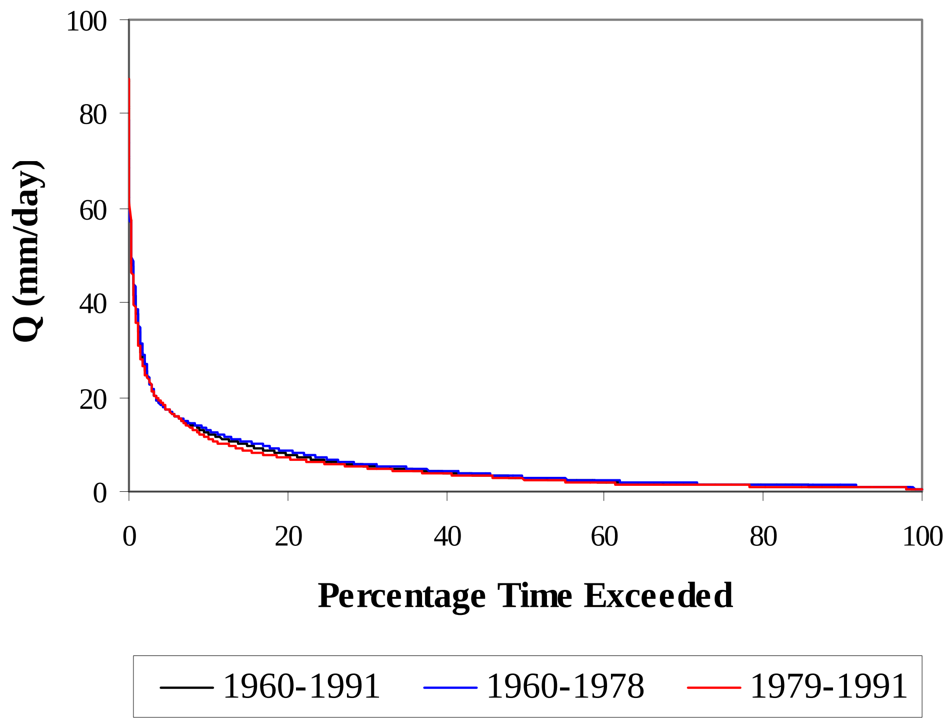
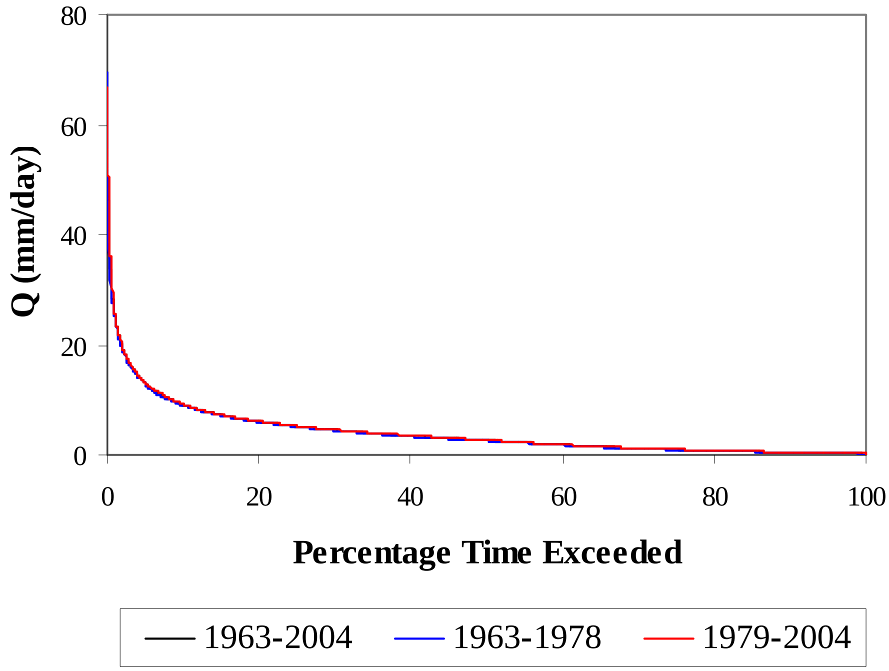


Figure 23. Flow duration curves of mean daily discharge, Caramávida river basin.

In Figure 24 the mean daily discharge flow duration curves for the Mulchén and Duqueco river basins are presented, following the same procedure described for Caramávida.



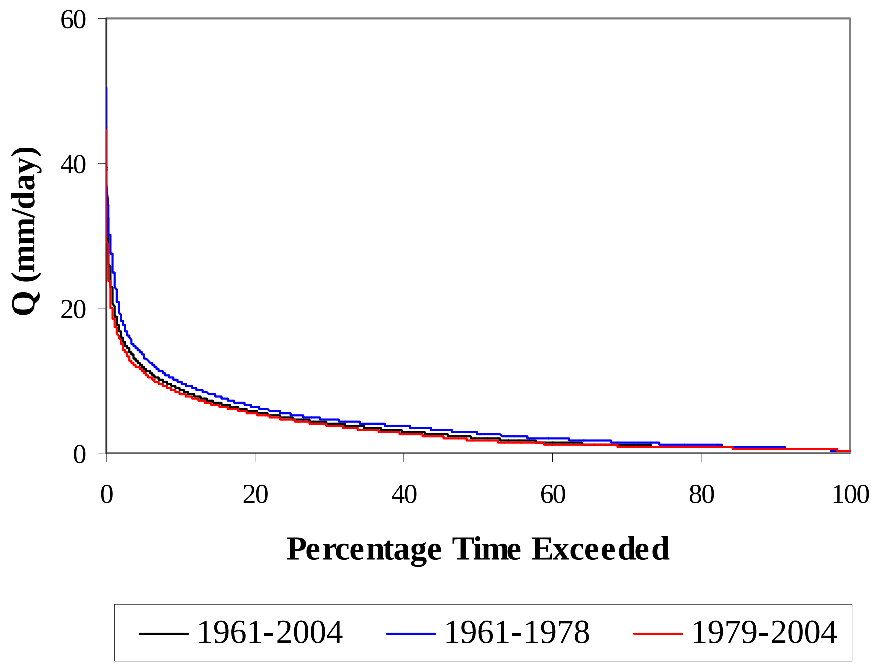


Figura 24. Mean daily discharge flow duration curves, Duqueco (above) and Mulchén (below) basins.

From the mean daily discharge flow duration curves of Figures 24 and 25, the mean daily discharges (50% of time discharge exceeded) and the daily discharges having 80 and 90% of time exceeded have been extracted for each river basin and every period (period before the change, after the change, and all year of records), Table 9.

Table 9. $Q_{50\%}$, $Q_{80\%}$ and $Q_{90\%}$ in Caramávida, Duqueco and Mulchén river basins, for different periods.

River basin	Period	$Q_{50\%}$		$Q_{80\%}$		$Q_{90\%}$	
		(mm/day)	Relative value	(mm/day)	Relative value	(mm/day)	Relative value
Caramávida	1960-1991	2.91	0.95	1.34	0.92	1.09	0.89
	1960-1978	3.07	1	1.46	1	1.23	1
	1979-1991	2.62	0.85	1.15	0.79	0.95	0.77
Duqueco	1963-2004	2.61	1.03	0.78	1.05	0.47	1.04
	1963-1978	2.54	1	0.74	1	0.45	1
	1979-2004	2.67	1.04	0.83	1.12	0.49	1.09
Mulchén	1961-2004	2.09	0.76	0.85	0.75	0.66	0.87
	1961-1978	2.75	1	1.13	1	0.76	1
	1979-2004	1.77	0.64	0.79	0.70	0.64	0.84

From Figures 23 and 24 and Table 9 it can be appreciated that in the Caramávida and Mulchén river basins the values for $Q_{50\%}$, $Q_{80\%}$ and $Q_{90\%}$ during the period starting in year 1979 are lower then the previous period ending in 1978 confirming the effect of the decrease in water production as a result of the increase of the area under forests. In Caramávida, $Q_{50\%}$ is reduced for period 1979-1991 to a 85% of the measured in period 1960-1978, whereas $Q_{80\%}$ and $Q_{90\%}$ are reduced to 79 and 77%, respectively, between both periods. In Mulchén, the greater reduction happens for $Q_{50\%}$ which in period 1979-2004 is a 64% of the measured in 1961-1978, whereas $Q_{80\%}$ and $Q_{90\%}$ are reduced to 70 and 84%, respectively, between both periods. For the Caramávida and Mulchén river basins, the differences between the mean daily discharge flow duration curves corresponding to the records of all the period of availability of data and those from the periods previous and subsequent to year 1978 are statistically significant (Kolmogorov-Smirnov test, $p < 0.05$).

In the case of the Duqueco river basin the situation is different, since the values of $Q_{50\%}$, $Q_{80\%}$ and $Q_{90\%}$ are higher for period after 1979, which that does not agree with the reduction in the water production that is detected since this year according to the analysis shown in the precedent Figure 23. Nevertheless, in Duqueco the differences between the mean daily discharge flow duration curves corresponding to the records of all the period of availability of data and those from the periods previous and subsequent to year 1978 are not statistically significant (Kolmogorov-Smirnov test, $p < 0.05$).

The analysis of the flow duration for the Caramávida, Duqueco and Mulchén river basins was repeated for the daily discharges of the low flow summer months (November to March), also considering the records of all the period of availability of data and those from the periods previous and subsequent to year 1978, Figure 25.

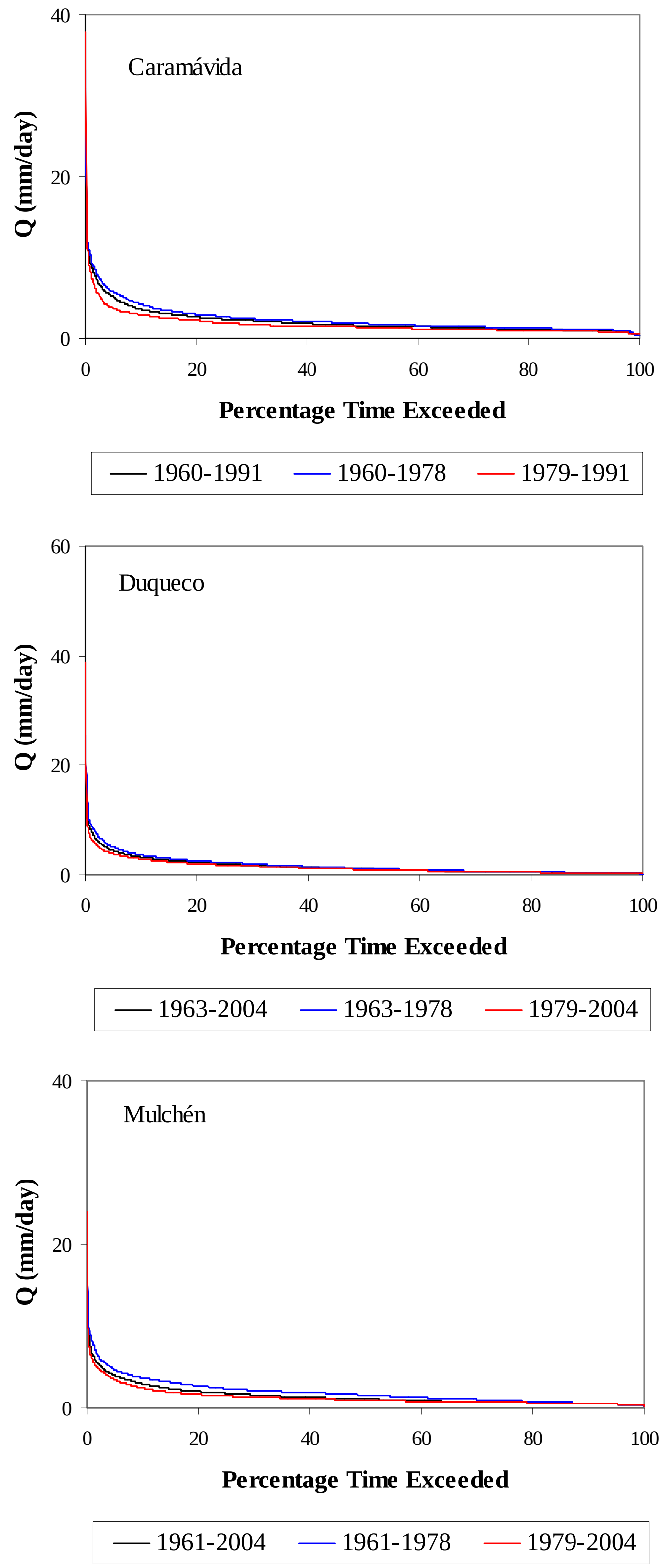


Figure 25. Mean daily discharge flow duration curves of the summer months (November to March), Caramávida, Duqueco and Mulchén basins.

As it was done for the daily discharges of the full year, from the mean daily flow duration curves generated from the summer months data (November to March) shown in Figure 25, for each river basin the values for $Q_{50\%}$, $Q_{80\%}$ and $Q_{90\%}$ for every period (before the change, after the change, and all the record) were selected, Table 10.

Table 10. $Q_{50\%}$, $Q_{80\%}$ y $Q_{90\%}$ of the low flow summer months (November to March) in the Caramávida, Duqueco and Mulchén basins, for the different periods.

River basin	Period	$Q_{50\%}$		$Q_{80\%}$		$Q_{90\%}$	
		(mm/day)	Relative value	(mm/day)	Relative value	(mm/day)	Relative value
Caramávida	1960-1991	1.62	0.86	1.16	0.88	0.97	0.83
	1960-1978	1.88	1	1.32	1	1.17	1
	1979-1991	1.41	0.75	1.00	0.76	0.92	0.79
Duqueco	1963-2004	1.05	0.88	0.48	0.92	0.35	0.92
	1963-1978	1.19	1	0.52	1	0.38	1
	1979-2004	0.97	0.82	0.45	0.87	0.34	0.89
Mulchén	1961-2004	1.10	0.69	0.69	0.83	0.56	0.93
	1961-1978	1.59	1	0.83	1	0.60	1
	1979-2004	0.97	0.61	0.67	0.81	0.55	0.92

In the three river basins the values of $Q_{50\%}$, $Q_{80\%}$ and $Q_{90\%}$ of the summer months are lower since year 1979 when compared with those from the 1963-1978 period. The higher reduction is noticed for the $Q_{50\%}$ value in the three river basins. The values of $Q_{50\%}$ represent periods in summer with a certain level of soil water availability which, since year 1979, is being consumed by the forests that cover important part of the total area of these three river basins. The values of $Q_{80\%}$ and $Q_{90\%}$ represent periods in summer of diminished soil water availability in the ground, in which the physiological activity of the trees is noticeably reduced then the effect of the increase of the afforested area on these low water flows seems to be smaller. This fact is quite important since $Q_{80\%}$ and $Q_{90\%}$ are used to define permanent and continuous Water Rights, those that should be being affected only marginally by the increase of the planted area, while the most affected possible water rights could be those of eventual character.

For the Caramávida, Duqueco and Mulchén river basins, the differences between mean daily flow duration curves of the summer months of corresponding to the records of all the period of availability of data and those from the periods previous and subsequent to year 1978 are statistically significant (Kolmogorov-Smirnov test, $p < 0.05$).

4.3. Extreme events and land use changes in experimental catchments

4.3.1 Peak flows for different forest cover conditions in the experimental catchments

Figure 26 illustrates the relationship between the size of rainfall events and the resultant peak flows at La Reina. This relationship was considered independently for the pre- and post-harvesting periods (1997 to 1999 and 2000 to 2002, respectively), and in these cases the r^2 values were 0.77 and 0.46 indicating moderate and lower correlation, respectively. The value of r^2 is lower for the pre-harvesting condition and reflects the higher variance between the size of rainfall event and peak flows as compare with the situation in the post-harvesting period. Peak flow generation processes are very much affected by antecedent moisture conditions and rain total, intensity and duration of each storm event. Type of vegetation influences rainfall interception and soil water retention. Deep rooted trees with spreading branches may induce variation in interception and retention that is not so pronounced in a more homogenous cover that occur after timber removal.

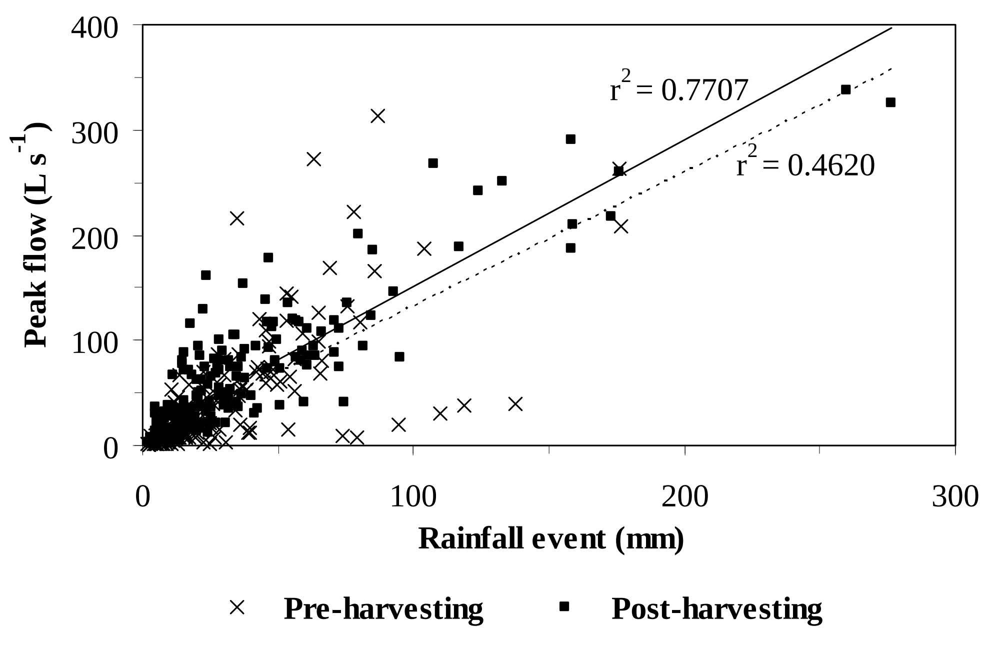


Figure 26 Peak flows at La Reina catchment (from Iroumé *et al.*, 2005).

At the La Reina catchment, mean peak flows for the pre- and post-harvesting periods were 48.3 and 63.8 l/s, respectively. This difference (statistically significant as determined by the *t*-statistic at a 95% level) represents a mean increase in peak flows of 32% after clearcutting the forest that covered the 79.4% of the area of this experimental catchment. On average, the volume of precipitation from individual rainstorms that generated these peak flows during the pre- and post-harvesting periods were not significantly different (*t*-statistic, 95% level), therefore supporting the hypothesis that the increases in peak flows are associated to the differences in land cover between the two periods.

The range of peak flow increases after timber harvesting were strongly correlated with the extension of the clearcut area within a catchment, and the 32% increase found in this research is rather low considering the harvested area at La Reina. Since afforestation effects in reducing peak flows is bigger for smaller storms (Fahey 1994, Calder 1992), then precipitation characteristics in the studied area (annual rainfall concentrated in winter months and intense events) explain the lower impact of changes in forest cover on peak flows. In this wet temperate region where the La Reina catchment is located, timber harvesting had a greater effect in increasing annual runoff compared to peak flows.

Figure 27 reveals the relationship between the size of rainfall events and the resultant peak flows at the Los Ulmos catchments, for the period 2000-2002. In each case the r^2 values were close to 0.6 indicating moderate correlation. Mean specific peak flows were 2.6 and 2.7 l/s/ha at Los Ulmos1 and Los Ulmos2, respectively, representing a non significant difference (*t*-statistic, 95% level) of 2.1%.

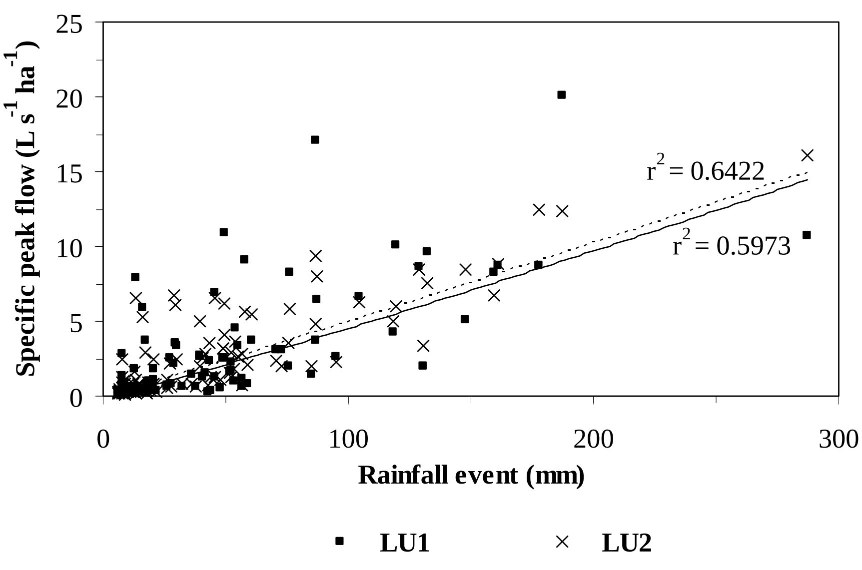


Figure 27. Peak flows at the Los Ulmos catchments (from Iroumé *et al.*, 2005).

Notwithstanding the differences in the area of forest cover between the two Los Ulmos catchments, the more developed plantation in Los Ulmos1 seems to have more effect on annual runoffs than in peak flows. Besides the influence of forest cover, the differences in size (Los Ulmos1 is smaller than Los Ulmos2), hillslopes (Los Ulmos2 is steeper than Los Ulmos1), drainage density (165 m/ha in Los Ulmos1 and 59 m/ha in Los Ulmos2) and forest road density (139 m/ha in Los Ulmos1 and 87 m/ha in Los Ulmos2) between the two catchments also affect peak flow processes.

The mean specific peak flow measured at La Reina during the period 2000-2002 (post-harvesting conditions) was 1.9 l/s/ha, lower than those registered in Los Ulmos1 and Los Ulmos2 (2.6 and 2.7 l/s/ha, respectively) for the same period. This disparity may be possibly explained in terms of size as La Reina is larger then the two Los Ulmos catchments.

4.3.2 Extreme event analysis at the La Reina catchment for the pre and post-harvesting periods

Peak flows at the La Reina catchment were analyzed separating the peak flows into categories based on rainfall-event volume ('small' rainfall events from 5 to 10 mm, "medium' events from 10 to 50 mm and 'large' events with rainfall volumes greater than 50 mm), Primrose (2004). Comparing post and pre-harvesting conditions, the percentage change for the 'large' event category is less than that resulting from both the 'medium' and 'small' event size categories as was hypothesized. This trend is revealed in graphical form in Figure 28, where the logarithmic scale used on the y-axis serves to illustrate the relative, proportional change in median values for each event size category, rather than the absolute change.

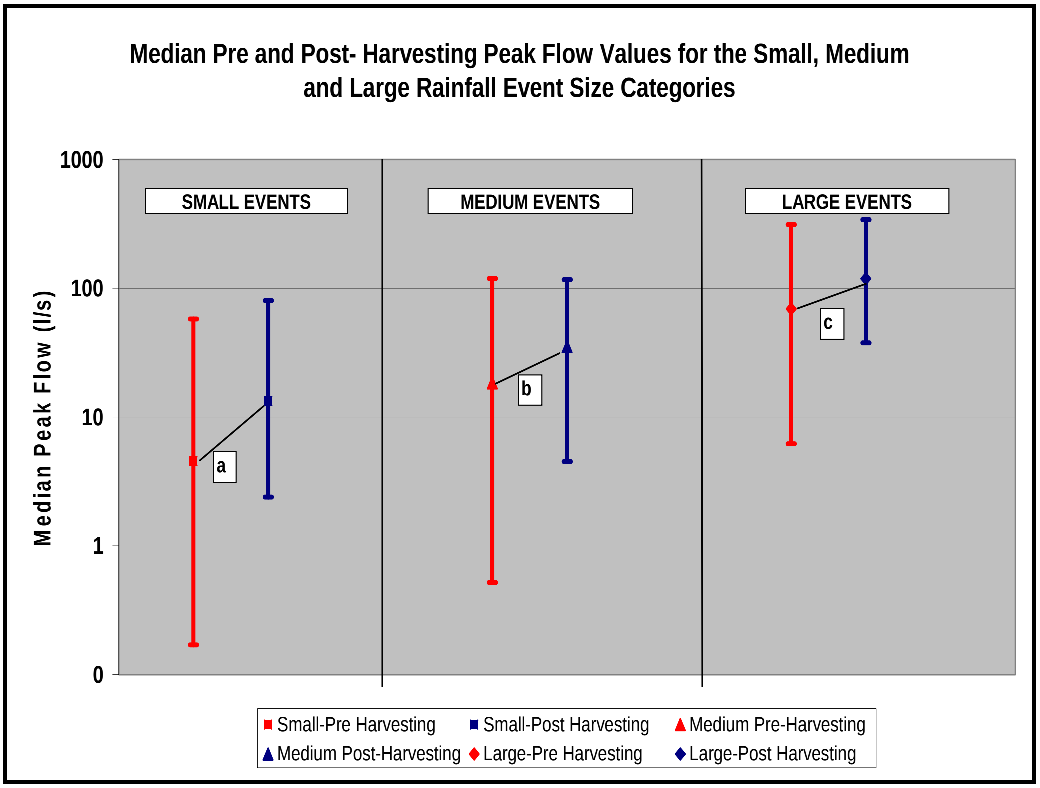


Figure 28. Graphical display of the differences in pre and post-harvesting median peak flow values for each rainfall event size category - the bars represent the maximum and minimum peak flow values for each category. Pre-harvesting period is between 1997 and 1999, post-harvesting from 2000 to 2003 (from Primrose, 2004)

From Figure 28 it can be observed that percentage increase in median peak flow values between the pre and post-harvesting periods is greatest within the ‘small’ events category as illustrated by line ‘a’, whilst the smallest percentage increase in median values is represented by line ‘c’ within the ‘large’ events category. This result is consistent with the theory that the ‘damping’ effect of forest cover on peak flow values is less prevalent during larger, more extreme rainfall events.

This analysis is expanded including peak flow data from 2005 and 2006, Table 11. The results presented in Table 11 show that in this catchment and for the three categories of rainfall-event size basis, the post-harvesting peak discharges are higher that those of pre-harvesting period (statistically significant differences), which indicates that the removal of the vegetal cover has a significant effect in the peak flows. Nevertheless, the increase in the discharges of the post-harvesting period in the “large” events is minor from those of the category “small”. This seems to confirm that the effect of the forest operations is of greater importance in events of smaller return periods.

Table 11. Median of peak flows for event size categories, for the pre-harvesting period and each year of the post-harvesting period, La Reina catchment.

	Year	Size of the rainfall event		
		Small	Medium	Large
Median of peak flows, pre-harvesting condition (l/s)	All	4.6	18.5	69.2
Median of peak flows, post-harvesting condition (l/s)	2000	13.8	29.8	101.3
	2001	11.7	29.5	180.2
	2002	14.2	46.6	100.6
	2003	13.1	41.2	154.9
	2005	20.7	41.2	99.4
	2006	14.9	42.6	108.3

Considering the first and the two last years after plantation harvesting in the La Reina catchment (years 2000, 2005 and 2006, respectively), the percentage increase in the median peak flow values for the Small, Medium and large rainfall event size categories are:

- Small events “: Pre-harvesting to year 2000, increase is 3 times; pre-harvesting to year 2005, increase is 4.5 times; and, pre-harvesting to year 2005, increase is 3.2 times.
- Medium events: pre-harvesting to year 2000, increase is 1.6 times; pre-harvesting to year 2005, increase is 2.2 times; and, pre-harvesting to year 2005, increase is 2.3 times.
- Large events: pre-harvesting to year 2000, increase is 1.5 times; pre-harvesting to year 2005, increase is 1.4 times; and, pre-harvesting to year 2005, increase is 1.6 times.

These results, together with the information displayed in Table 11, show that in spite of the development of the new plantation established in year 2000, peak discharges registered in the sixth year after are still significantly higher to those of the pre-harvesting period.

In order to observe these results in graphical form and to be able to visualize some tendency, the values of the peak flow medians of every period and event size appear in Figure 29.

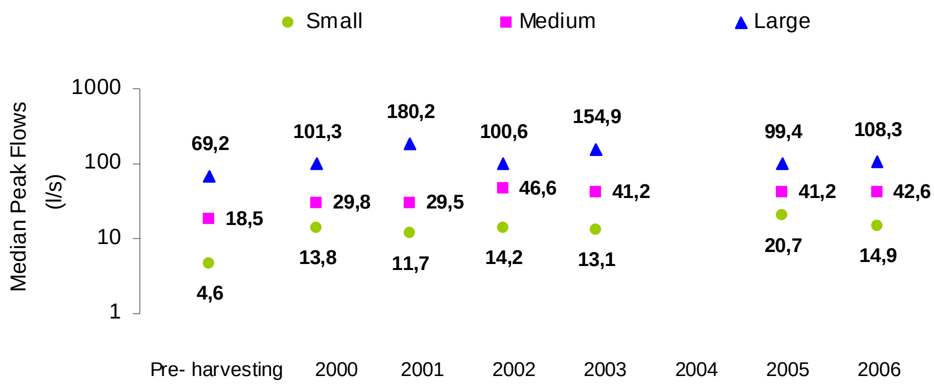


Figure 29. Trends of median peak flow values for the pre-harvesting and each year of the post-harvesting periods, La Reina catchment (Iroumé et al., 2006, plus additional data)

From Table 11 and Figure 29 it is possible to observe that the changes in the peak flow values during the first years after the removal of the plantation do not show an initial important increase followed of a gradual diminution tending towards the peak discharge levels of the pre-harvesting condition. There is no a consistent pattern for none of the categories of event sizes, and it is not either possible to notice, for example, a particular year of the post-harvesting period where all the peak flow medians have reached a “maximum”.

Peak flow medians for 2006 are still higher than those from the pre-harvesting conditions. Although runoff in La Reina has initiated in 2006 a reduction tending towards the levels of the pre-harvesting condition (see Figure 12), this is not yet the case of the peak flows.

Flow duration curves were calculated for each of the pre and post-harvesting years (1997 to 1999 and 2000 to 2003, respectively) at the La Reina catchment. The behavior of this catchment was performed comparing the change in the $Q_{10\%}$ high flow values illustrated on a flow duration curve. It may be questioned as to why the $Q_{10\%}$ value was adopted and not the $Q_{0\%}$ value. The justification for this decision is based on the conclusion that the extreme $Q_{0\%}$ flow is likely to exhibit considerable variability and thus may not be representative of a characteristic high flow.

In order to construct a curve for each year in the period of study, the hourly discharge data was aggregated to daily totals in litres/second and then ordered to give the percentage of the year for which each discharge was exceeded; the curves are displayed in Figure 30. From this figure it can be seen that there is a definite upward 'shift' of the $Q_{10\%}$ value in the post-harvesting years, with a maximum $Q_{10\%}$ value of 2000 l/s occurring in 2000 compared with a minimum $Q_{10\%}$ value of 500 l/s in 1998.

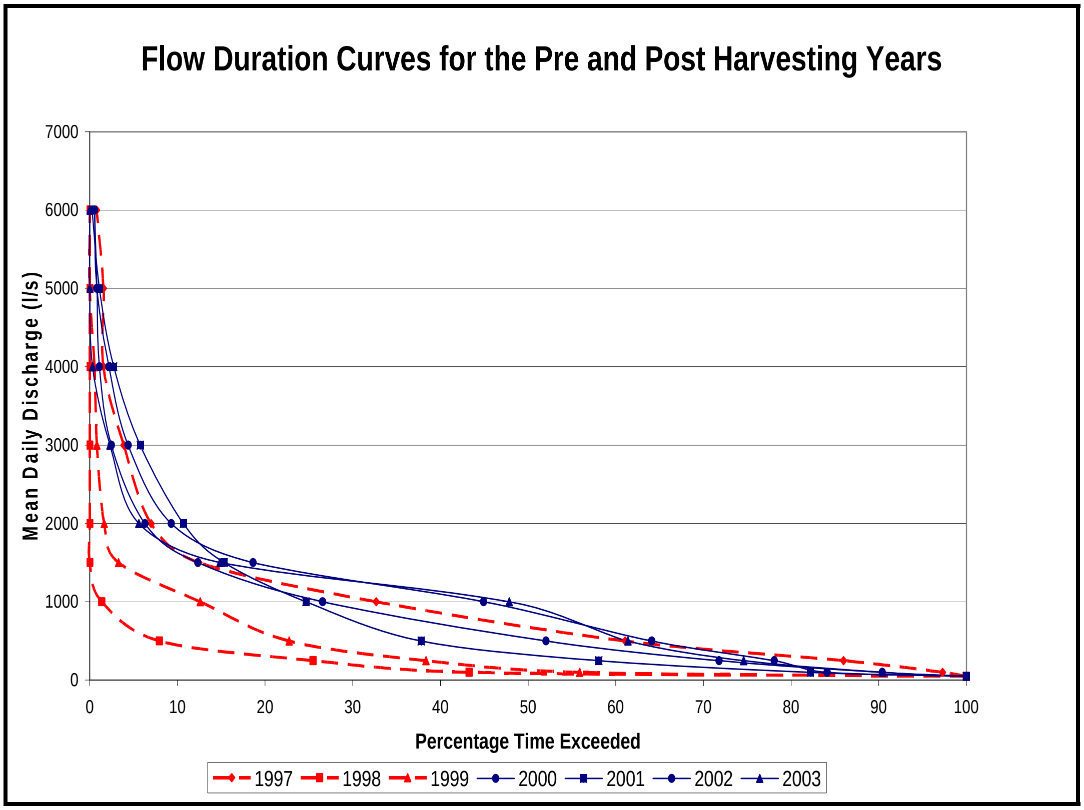


Figure 30. Flow duration curves for each of the pre and post-harvesting years (period 1997-2003).

In an attempt to examine this idea in more detail, further consideration was given to the pre and post-harvesting peak flow values arising from extreme rainfall events exceeding 100 mm in total precipitation (the upper section of the 'Large' event size category). In total, across the period of data analysis (1997 to March 2007), only 36 precipitation events exceeded this rainfall total-9 in the pre-harvesting period and 27 in the post-harvesting period.

Figure 31 reveals the relationship between these extreme events and the resultant peak discharge values.

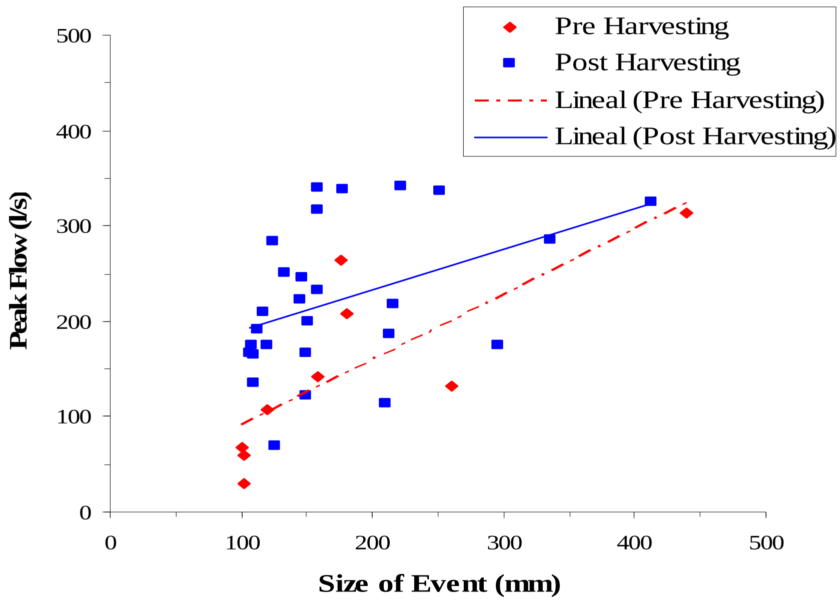


Figure 31. Pre and post-harvesting relationship between precipitation events greater than 100 mm and resultant peak discharge.

The trend from Figure 31 and extrapolation of the relationship to increasingly larger rainfall event sizes does appear to suggest that at the scale of extreme events, the corresponding peak flow values from pre and post-harvesting land cover conditions do not differ considerably. This result appears consistent with the suppositions regarding peak flows and extreme events.

A question still to be answered is how extremes are the extreme events recorded at the La Reina catchment. The following peak flow record is available in this catchment, Table 12.

Table 12. Peak flows, La Reina catchment.

Year	Instantaneous peak flow		Mean daily peak flow	
	Q (m^3/s)	Date	Q (m^3/s)	Date
1997	0.313	28-07-97	0.255	28-07-97
1998	0.039	09-04-98	0.033	15-08-98
1999	0.263	09-08-99	0.152	09-08-99
2000	0.325	02-06-00	0.240	03-06-00
2001	0.342	17-07-01	0.275	07-01-01
2002	0.337	12-10-02	0.318	12-10-02
2003	0.340	19-06-03	0.163	20-06-03
2004	-	-	-	-
2005	0.179	30-07-05	0.116	30-07-05
2006	0.296	24-07-06	0.230	24-07-06

By means of a frequency analysis (Gumbel) the return periods associated to these maximum discharges are determined, and are graphically summarized in Figure 32.

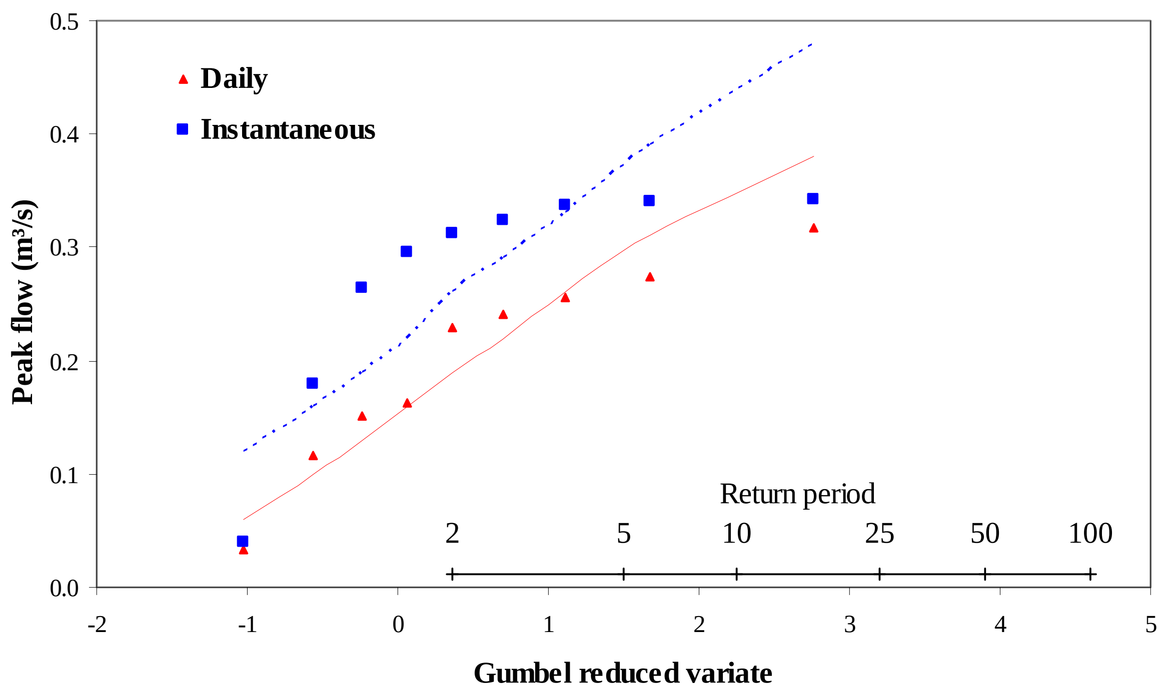


Figure 32. Instantaneous peak flow return periods, La Reina catchment.

For the period of information availability, the maximum measured instantaneous discharge in the La Reina catchment was 0.342 m^3/s, registered the 17th of July, 2001, and the corresponding return period is 10 years. In year 2002 the maximum measured instantaneous discharge was 0.337 m^3/s (the 12th of October) with an associated return period of 3.3 years.

It is difficult to interpret the turn out of the Gumbel analysis to define return periods to the La Reina peak flows, because of the short available data record. The records of years 2001 and 2002 are considered to expand the peak flow analysis in this experimental catchment. From the frequency analysis of the rainfall data of the Isla Teja (Valdivia) and Remehue (Osorno) stations, the return periods associated to annual and maximum 24-hour precipitations are determined, Figures 33 and 34.

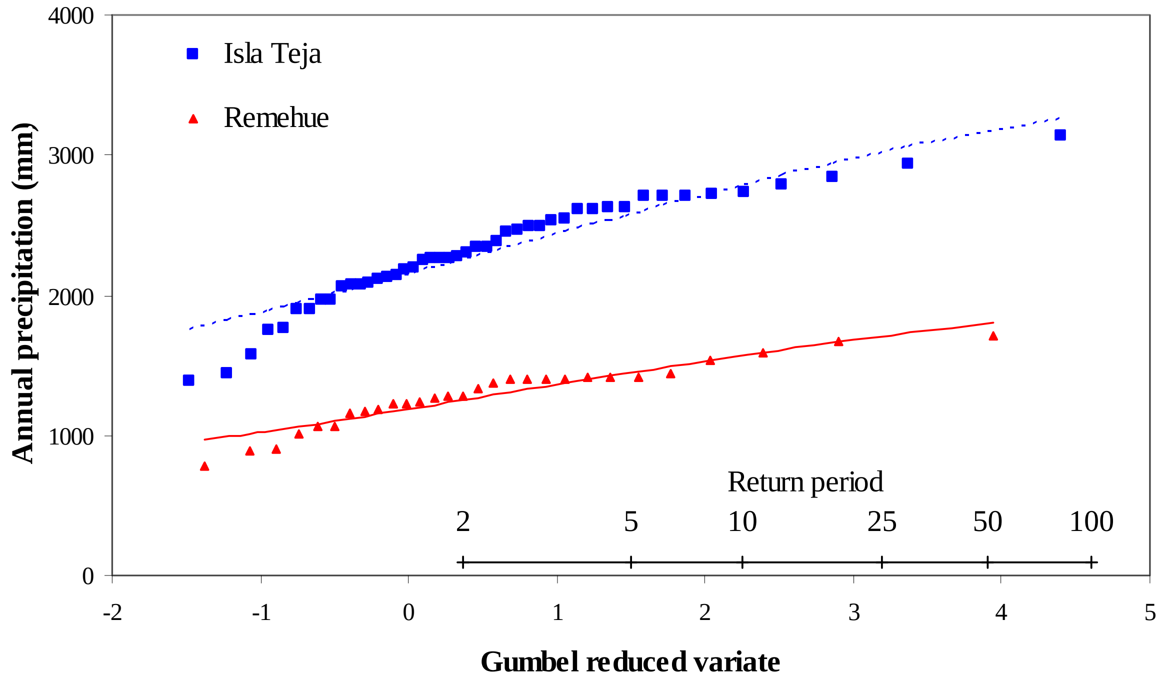


Figure 33. Annual rainfall return periods, Isla Teja and Remehue stations.

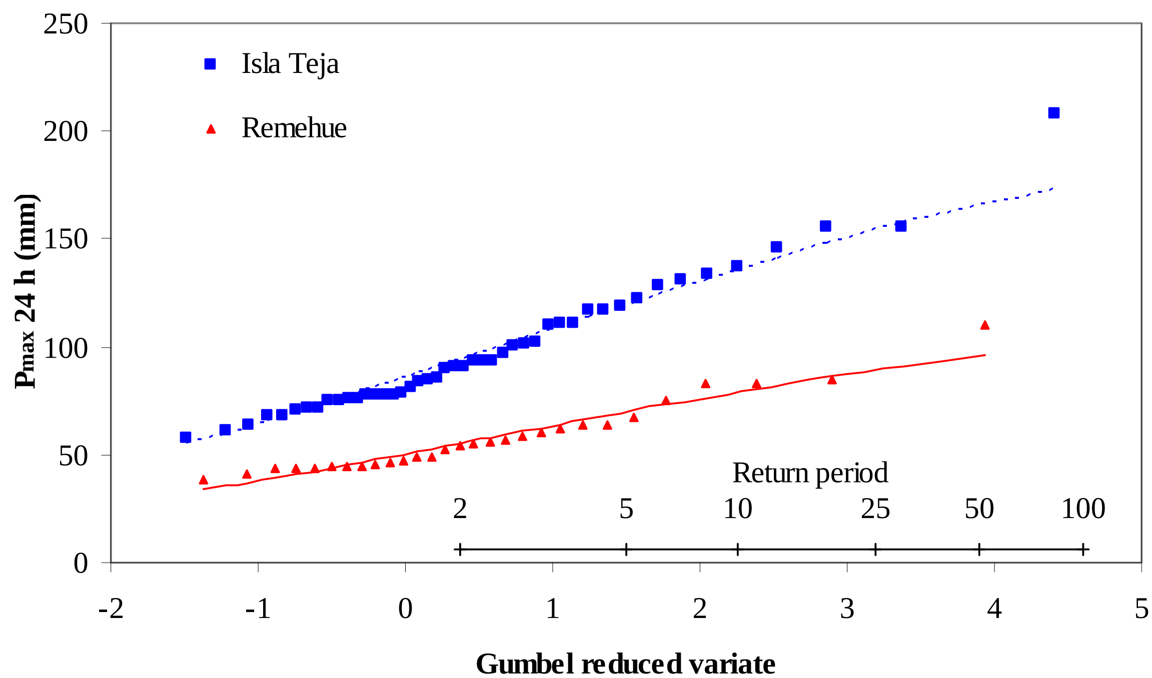


Figure 34. Maximum 24-hour rainfall return periods, Isla Teja and Remehue stations.

In both figures it is possible to appreciate that for a given return period both annual and maximum 24-hour precipitations are higher in Isla Teja than in Remehue. From these analyzes, the return periods corresponding to the records of years 2001 and 2002 in these two pluviometric stations are determined, Table 12.

Table 12. Detail of the frequency analysis at the Isla Teja and Remehue rainfall stations: results for years 2001 and 2002.

Year 2001

	Maximum 24 hours rainfall			Annual precipitation	
Station	P_{max} 24h (mm)	Date	Return period (years)	P (mm)	Return period (years)
Isla Teja	102.4	08/07/2001	2.6	2245.7	2.0
Remehue	48.8	26/05/2001	1.5	1270.3	2.0

Year 2002

	Maximum 24 hours rainfall			Annual precipitation	
Station	P_{max} 24h (mm)	Date	Return period (years)	P (mm)	Return period (years)
Isla Teja	155.7	12/10/2002	22	3140.2	29
Remehue	83.3	01/10/2002	12	1668.1	15

In the case of year 2001, the annual and maximum 24-hour precipitation records correspond, both at Isla Teja and Remehue, to return periods of the order of 2 years. This means that the highest peak flow recorded in La Reina (with a period of return of the order of 10 years) occurred in a year that was not particularly rainy in the zone where this catchment is located. In 2002, the maximum 24-hour and the annual precipitations have return periods 22 and 29 years in Isla Teja and of 12 and 15 years in Remehue, which indicate that in a rainy year for the study zone the maximum recorded peak flow in La Reina in 2002 has a smaller return period than the one registered in year 2001.

The analysis of the La Reina peak flows is completed, for years 2001 and 2002, of the revision of the maximum daily discharges registered in larger river basins in the area where this experimental catchment is located. The records of the Cruces in Rucaco, Iñaque in Máfil, Collilelfu in Los Lagos, Damas in Tacamó and Negro in Chahuilco stations are used (stations number 13, 14, 15, 17 and 18, Figure 2 and Table 6), to assign return periods (Gumbel analysis) to the maximum discharges of years 2001 and 2002, Table 13.

Tabla 13. Peak flows in years 2001 and 2002 and return periods in selected river basins in the Valdivia-Osorno area (La Reina included)

Basin-station	Area	Year 2001			Year 2002		
		Q_{max}[a]	Date	Return period	Q_{max}[a]	Date	Return period
	(km^2)	(m^3/s)		(years)	(m^3/s)		(years)
La Reina	**0.342**	**0.342**	**17/07/2001**	**10**	**0.337**	**12/10/2002**	**3.3**
Collileufu-Los Lagos	581.0	257.0	08/06/2001	2.9	416.0	13/10/2002	15.4
Iñaque-Mafil	424.0	144.0	09/06/2001	2.9	249.0	13/10/2002	16.4
Cruces-Rucaco	1740.0	677.0	09/06/2001	3.5	821.0	14/10/2002	8.7
Damas-Tacamo	408.0	48.3	28/05/2001	1.2	113.0	13/10/2002	4.3
Negro-Chahuilco	2318.0	437.0	17/07/2001	2.6	682.0	13/10/2002	7.6
Sto. Domingo-R. de Piedra	127.0	92.3	08/07/2001	2.1	189.0	12/10/2002	9.9

[a] Q_{max} for La Reina is instantaneous peak flow and mean daily peak flow for the other basins.

In all these river basins but La Reina, the maximum discharges of year 2001 have return periods between 1 and 3 years, of the same order that the annual and maximum 24-hour precipitations at the Isla Teja and Remehue stations in that year. For year 2002, the return periods of the registered maximum discharges in these larger river basins are superiors to those of year 2001, the exception being again La Reina. In addition, it draws attention that all the peak flows (including the one registered in La Reina) were generated by the same storm (all the maximum discharges were recorded between October 12 and 14, 2002).

Looking at the return periods of the peak flows registered in the larger basins in years 2001 and 2002 (Table 13), it is possible to assign to the La Reina highest registered peak flows return periods in the range of 4 to 16 years (in the order of 10 years, in average).

Under these circumstances, peak flow values from pre and post-harvesting land cover conditions at La Reina only differ for events with return periods clearly lower than 10 years. The trend from Figure 31 and this extreme event analysis at the La Reina catchment seem to suggest that for 10-year and larger return period extreme events, peak flows from pre and post-harvesting land cover conditions do not differ considerably which supports the hypothesis that, as the size of the flood peak increases, the effect of land use becomes less important.

4.4. Extreme events and land use changes in large river basins

4.4.1 Peak flow analysis in large river basins

The maximum discharges in the Caramávida, Duqueco and Mulchén river basins were analyzed. For these three river basins return periods were assigned (Gumbel frequency analysis) to the daily maximum discharges using the records of all the period of availability of data and those from the periods previous and subsequent to year 1978, in which a break in the water production trend has been detected (see Figures 21 and 22).

The result of this analysis for the Caramávida the river basin is graphically shown in Figure 35. On the other hand, Figure 36 presents the results for the Duqueco and Mulchén river basins.

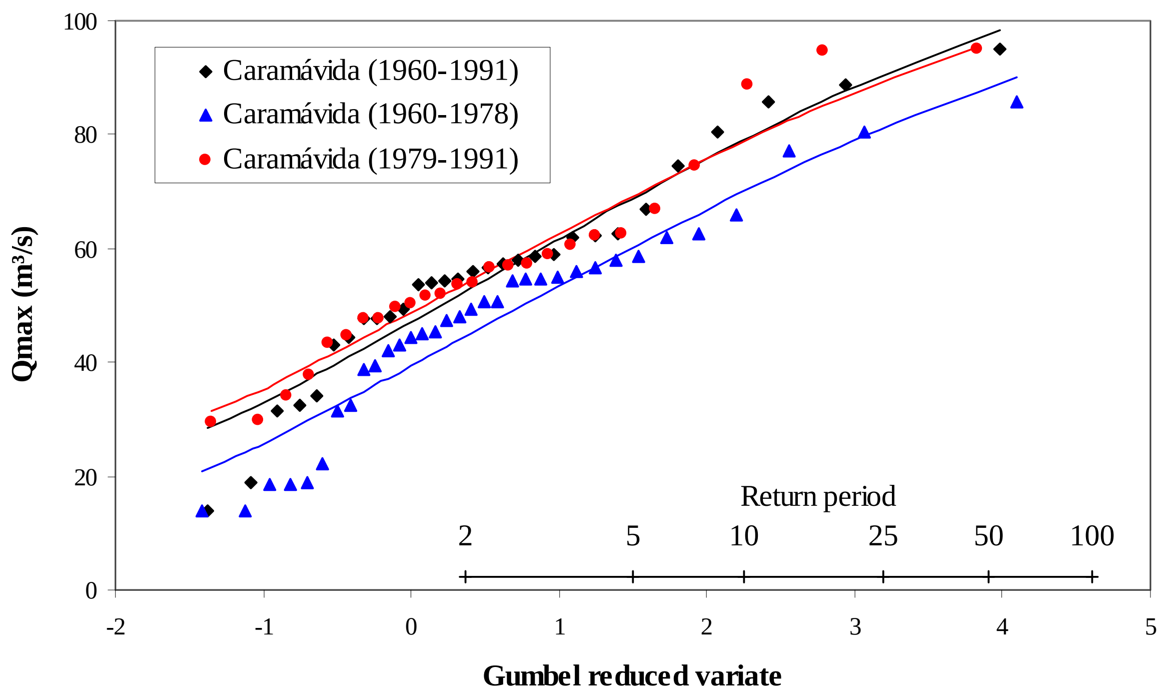


Figure 35. Daily peak discharge return periods for all the period of availability of data and those from the periods previous and subsequent to year 1978, Caramávida river basin.

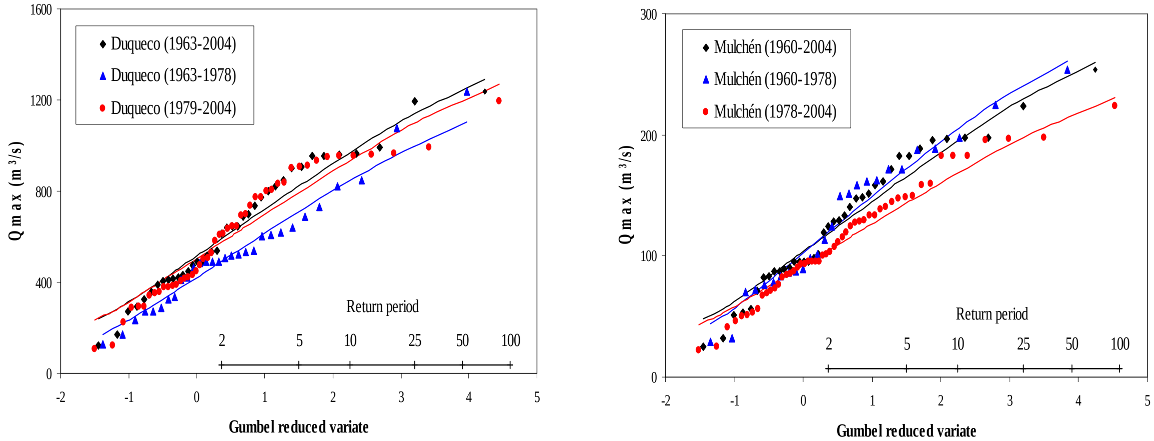


Figure 36. Daily peak discharge return periods for all the period of availability of data and those from the periods previous and subsequent to year 1978, Duqueco and Mulchén river basins.

In the case of the Caramávida and Duqueco river basins, for a same return period the daily maximum discharges from the "after year 1979" period are superiors that the corresponding ones to "before year 1978". This would be indicating that the development of the plantations in these river basins, that generated a reduction in water production, does not reduce the levels of peak discharges.

In the case of the Mulchén river basin, the daily maximum discharges are smaller in the period of forest development, indicating a potential effect of afforestation in decreasing both water yield and peak flows.

However, the three curves (in Figures 35 and 36) generated by means of the Gumbel analysis for these three river basins do not show statistically significant differences (Kolmogorov-Smirnov test). This could be indicating that the increase of the afforested area would be affecting only marginally the levels of peak flows, when comparing the data from the periods before and after the development of the plantations.

Table 14 presents the daily maximum discharges in the Caramávida, Duqueco and Mulchén river basins with return periods of 5, 10, 25 and 100 years, obtained using the records of all the period of availability of data and those from the periods previous and subsequent to year 1978.

Table 14. Five, 10, 25 and 100 year return period peak flows, Caramávida, Duqueco and Mulchén basins.

River basin	Period	$Q_{max\ T=5}$ (mm/day)	$Q_{max\ T=10}$ (mm/day)	$Q_{max\ T=25}$ (mm/day)	$Q_{max\ T=100}$ (mm/day)
Caramávida	1960-1991	63.9	74.2	87.3	106.6
	1960-1978	55.8	65.7	78.2	96.7
	1979-1991	64.4	74.2	86.7	105.1
Duqueco	1963-2004	46.4	55.2	66.4	82.9
	1963-1978	40.2	48.6	59.2	74.9
	1979-2004	44.7	52.9	63.4	78.9
Mulchén	1961-2004	33.2	39.6	47.6	59.5
	1961-1978	34.8	42.1	51.2	64.8
	1979-2004	28.8	34.0	40.6	50.4

The results that appear in Table 14 for the Caramávida and Duqueco river basins confirm what was previously mentioned in relation that peak discharges of the period of greater development of the afforested area are majors to the maximum discharges of the previous period.

Table 15 shows the variation (in percentage) of the peak discharges taking the period “before year 1978” as reference.

Table 15. Variation (in %) of peak flows having return periods of 5, 10, 25 and 100 years in the Caramávida, Duqueco and Mulchén basins (reference period, the previous to year 1978).

River basin	Period	Variation $Q_{max\ T=5}$ (%)	Variation $Q_{max\ T=10}$ (%)	Variation $Q_{max\ T=25}$ (%)	Variation $Q_{max\ T=100}$ (%)
Caramávida	1960-1991	14.44	12.94	11.61	10.27
	1960-1978	0	0	0	0
	1979-1991	15.30	12.95	10.84	8.71
Duqueco	1963-2004	15.43	13.71	12.23	10.79
	1963-1978	0	0	0	0
	1979-2004	11.20	9.04	7.18	5.38
Mulchén	1961-2004	-4.54	-5.92	-7.10	-8.23
	1961-1978	0	0	0	0
	1979-2004	-17.38	-19.16	-20.71	-22.19

These results are contradictory and they do not allow concluding on a potential reduction of the maximum peak flows after an increase of the afforested area in large river basins.

Daily peak flows from two specific pair of years in the pre and post-plantation development periods were compared at the Caramávida river basin. Two pairs of characteristic years with similar annual rainfall totals were chosen using the rainfall data from the Cañete station; one pair of rainy years and one of dryer years.

The first pair included 1975 (from the pre-plantation development period) and 1984 (from the post-plantation development period) with 1457 and 1528 mm/year, respectively. These two rainy years were preceded by dry years (1974 with 1182 mm/year and 1983 with 897 mm/year).

The second pair considered the dry years 1974 (from the pre-plantation development period) and 1986 (from the post-plantation development period) with 1183 and 1277 mm/year, respectively. These two years were also preceded by dry years (1973 with 1144 mm/year and 1985 with 1217 mm/year).

Flow duration curves were calculated for each of these two pairs, Figures 37 and 38.

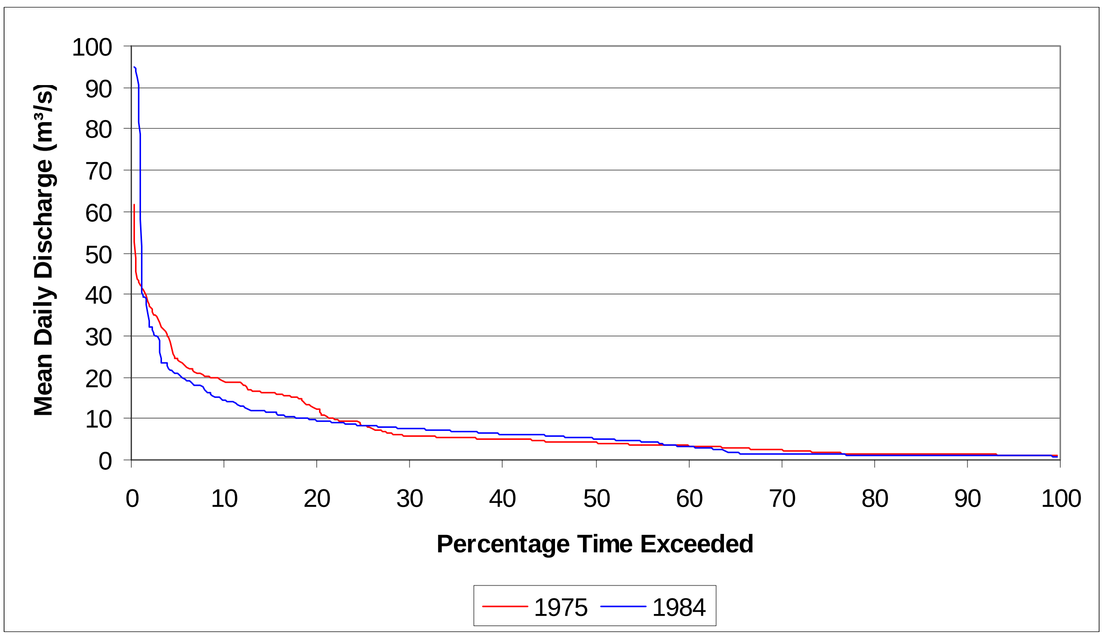


Figure 37. Flow duration curves for two specific rainy years at Caramávida.

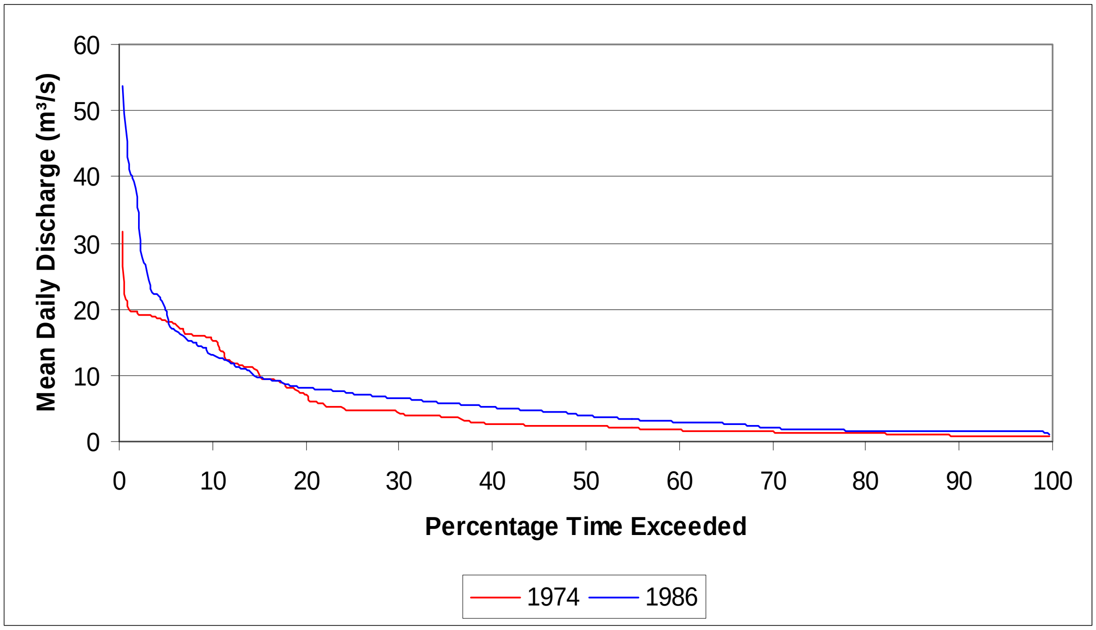


Figure 38. Flow duration curves for two specific dry years at Caramávida.

The behavior of this catchment was performed comparing the change in the $Q_{10\%}$ high daily flow values illustrated on the two flow duration curves. In the wetter condition, $Q_{10\%}$ value is 19 m^3/s in 1975 and 14 m^3/s in 1984, while in the dryer condition $Q_{10\%}$ is 15 m^3/s in 1974 and 13 m^3/s in 1986. From these figures it can be seen that there is downward ‘shift’ of the $Q_{10\%}$ value in the post-plantation development years indicating that the increase of the forested area do as an effect in reducing peak discharges.

A frequency analysis (Gumbel) of maximum 24-hour precipitations was realized in the Los Angeles, Collipulli, Cañete and Trupán pluviometric stations (these stations, together with Laguna Malleco and Temuco were used to characterize the precipitation pattern of the area where the large river basins analyzed in this report are located). This analysis realized for the periods previous and subsequent to year 1978 and with every year of the series of precipitation records is presented in Figure 39.

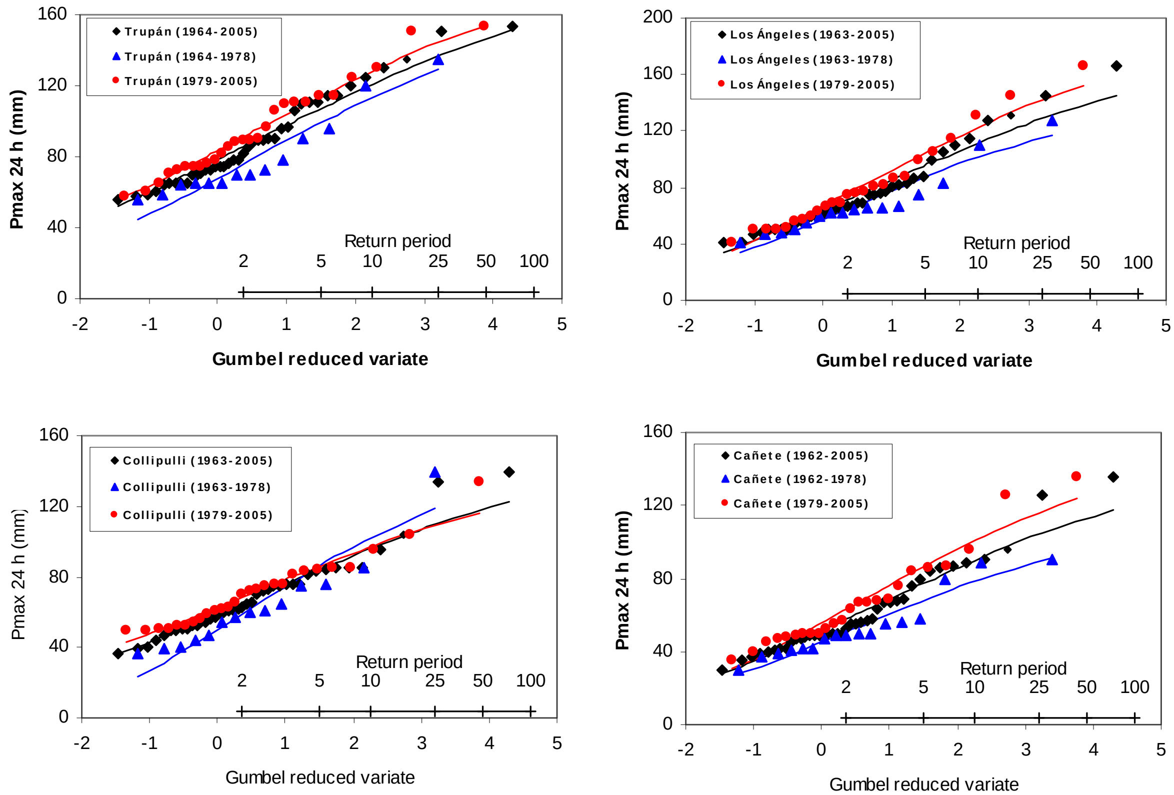


Figure 39. Return periods of maximum 24-hour precipitations, Trupán, Los Angeles, Collipulli and Cañete stations, for all the period of availability of data and those from the periods previous and subsequent to year 1978.

In the Los Angeles, Cañete and Trupán stations, maximum 24-hour precipitations are higher for the period "after year 1979", whereas for the Collipulli station it happens the opposite.

To analyze peak flows at the Caramávida, Duqueco and Mulchén river basins, to the effect of the increase of the afforested area it is necessary to add the corresponding to the variations from one period to the other in the intensity pattern of the precipitations that generate these peak flows, which coincide with the findings of Pizarro *et al.* (2006). Because rainfall is not uniform over a large area even during large storms, differences in areal distribution of precipitation among storms and study periods can add to the variability of peak flows when comparing the periods "before year 1978" with "after year 1979".

4.4.2 Extreme event analysis at the Caramávida, Duqueco and Mulchén river basins

In an attempt to examine this idea in more detail, i.e. the joint and contradictory effect of increase of forested area and increase in rainfall intensity since 1979 in the Caramávida, Duqueco and Mulchén river basins, further consideration was given to the pre and post-plantation development peak flows. For each of these three basins several pair of storms (one storm from the pre-plantation development period and one from the post-plantation development period) were identified. Each pair was chosen in terms of similar total event precipitation and accumulated rainfall for the previous 7 and/or 14 days. Figures 40, 41 and 42 reveal the relationships between these rainfall events and the resultant peak discharge values for the three river basins.

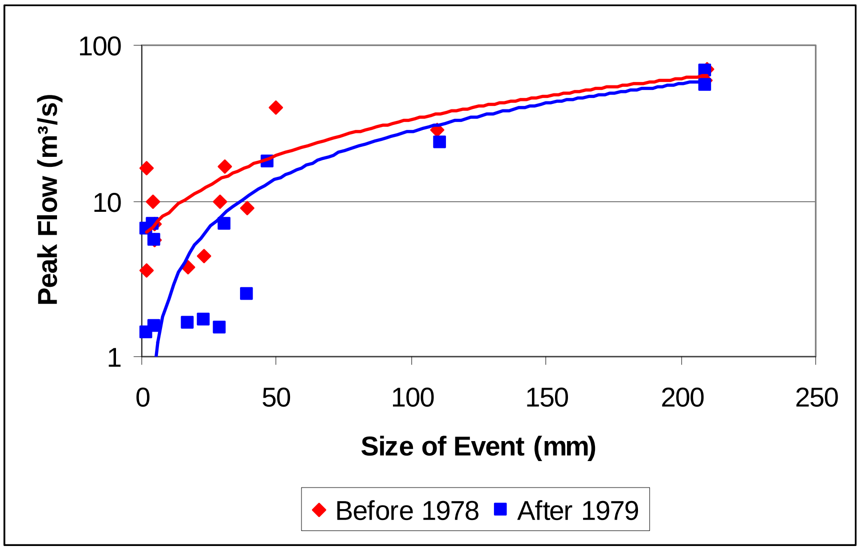


Figure 40. Pre and post-plantation development relationships between pairs of precipitation events and resultant peak discharges, Caramávida river basin.

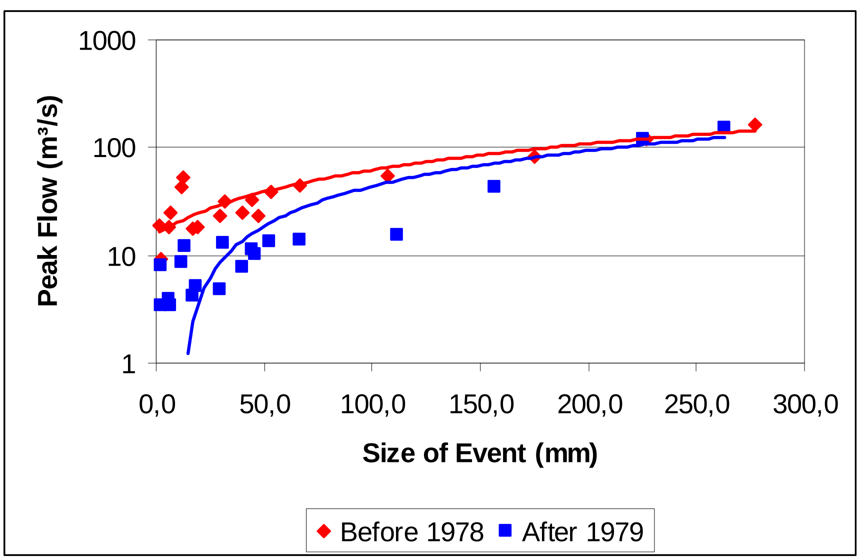


Figure 41. Pre and post-plantation development relationships between pairs of precipitation events and resultant peak discharges, Mulchén river basin.

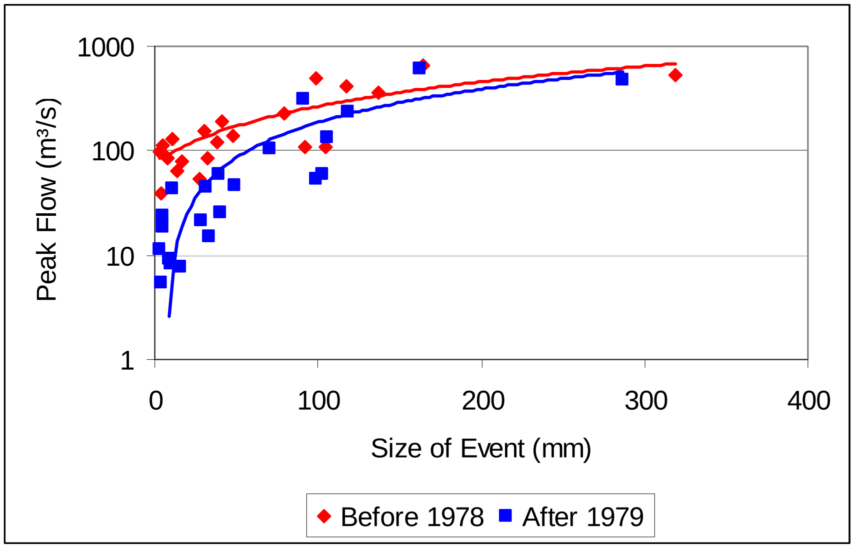


Figure 42. Pre and post-plantation development relationships between pairs of precipitation events and resultant peak discharges, Duqueco river basin.

The trends from Figures 40, 41 and 42 and extrapolations of the relationships to increasingly larger rainfall event sizes do appear to suggest that at the scale of extreme events, the corresponding peak flow values from pre and post-plantation development land cover conditions do not differ considerably. Figures 43, 44 and 45 present the comparisons of the resultant peak flows from each of the event pairs and from each of the three studied river basins.

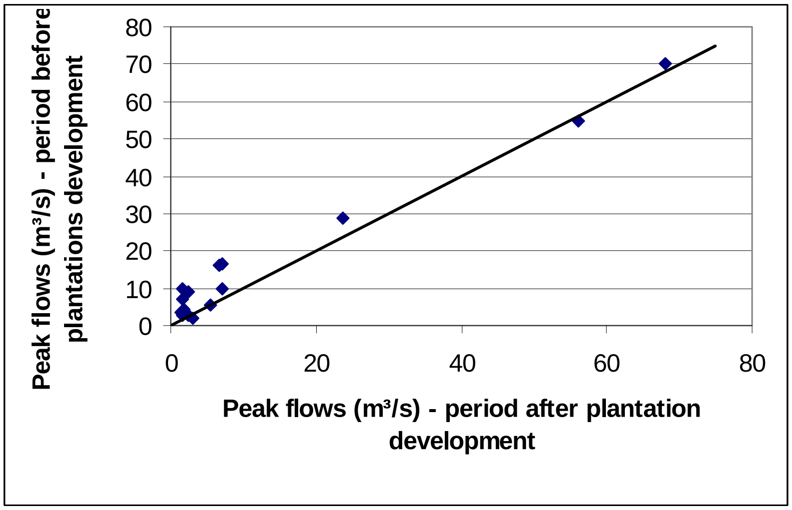


Figure 43. Comparison of resultant peak flows from event pairs, Caramávida river basin.

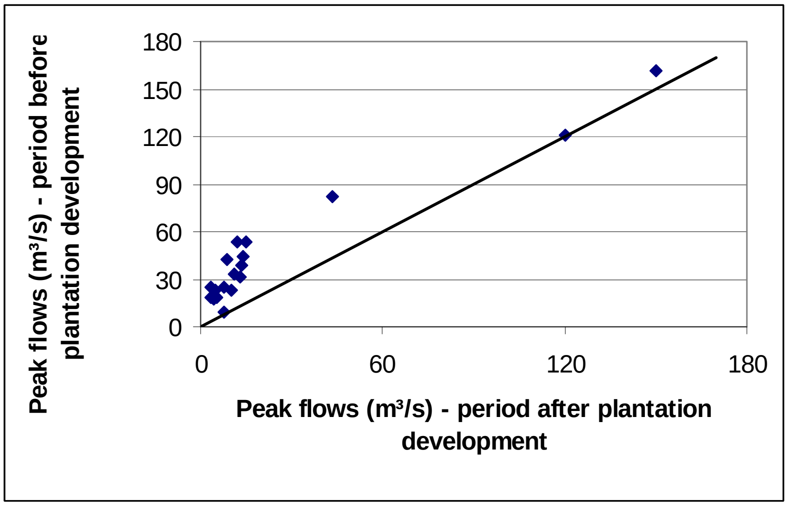


Figure 44. Comparison of resultant peak flows from event pairs, Mulchén river basin.

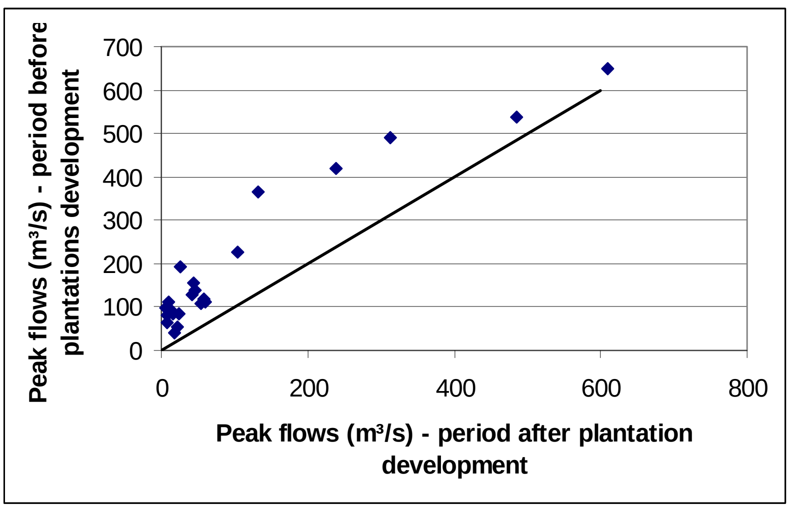


Figure 45. Comparison of resultant peak flows from event pairs, Duqueco river basin.

The comparisons presented in Figures 43, 44 and 45 indicate that, for similar rainfall conditions, peak flows generated in events during the period before the increase of planted area are consistently higher than those from the period subsequent to 1978. But from the same figures it is possible to conclude that as peak flow size increases the corresponding peak flow values from pre and post-plantation development land cover conditions do not differ considerably.

At the Caramávida river basin, the differences in peak flow values from pre and post-plantation development differ considerably only for peak flows lower than 60 m^3/s. This level of peak flow corresponds to return period between 2 and 5 years (data extracted from Figure 35).

At the Mulchén and Duqueco river basins, peak flows from the pre and post-plantation development periods differ significantly for peak flows lower than 120 and 500 m^3/s, respectively. The corresponding return periods for these peak flow values are in the order of 2 to 5 years (from Figure 36).

In these river basins, peak flow values from pre and post-plantation development conditions only differ for events with return periods lower than 5 years. These results appear consistent with the suppositions regarding peak flows and extreme events and the findings for the smaller experimental catchments.

4.5. Sediment transport in experimental catchments

Monthly suspended sediment loads (TSS, ton/ha) for catchments Los Ulmos 1 and 2 and Aragón 1 and 2 are shown in Figure 46.

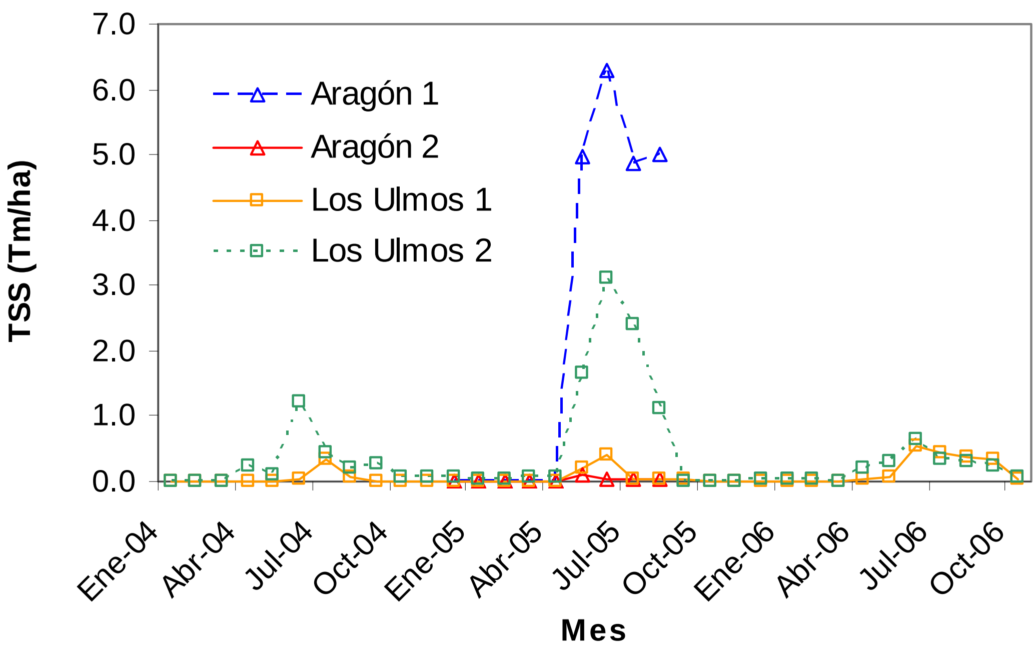


Figure 46. Monthly suspended sediment load in experimental catchments.

In the period January 2004 to October of 2006 it can be appreciated that at the Los Ulmos 1 and 2 catchments, the monthly suspended sediment transport is only significant during July, associated to the periods of major precipitations and runoffs. The value of 3 ton/ha registered in Los Ulmos 2 in July 2005 seems quite high considering that none forest operations took place during the study period in this catchment.

The plantation of the Aragon 1 catchment was clearcut in winter since April 2005, situation that explain the important increase of suspended sediment load as compared with the sediment load from the neighbouring and undisturbed Aragon 2 catchment. In July 2005, the Aragon 1 catchment monthly suspended sediment load was 6 ton whereas in Aragon 2 monthly suspended load was 6 ton. The investigation in the two Aragon catchments could not continue beyond September 2005, because the amount of sediment transported damaged the instruments and made collapse irreversibly the gauging section. Most of the sediment transport in the Aragon1 catchment originated from cut and fill forest road slopes, in a watershed were the riparian vegetation and buffer protection zones were practically nonexistent.

The increases in sediment load after clearfelling can be defined as extreme events not generated by intense rainfalls but associated to plantation forest operations. This reinforces the proposals that the EPIC-UACh group, within the framework of best management practices and definition of standards for harvesting and road planning, has been raising in forums and discussion groups[1].

4.6. Hydrological simulation scenarios in experimental catchments

4.6.1 Management scenarios analysis at La Reina using SHETRAN

The La Reina area model was generated using the existing SHETRAN physically based, spatially distributed catchment modelling system. Calibration was completed for this catchment for two separate periods: firstly, for 1996-1999 with mature plantation forest; and secondly, for 2000-2001 with vegetation appropriate for a logged forest.

Details of SHETRAN application to the La Reina catchment are presented in Birkinshaw and Bathurst (2007), in the D14 of this EPIC Project.

[1] Correspond to the “Policy issues” proposed by the UACh-EPIC group.

4.6.2 Simulation analysis at Los Ulmos2 using WaSIM

The Los Ulmos2 area model was generated using the existing WaSiM-ETH (**W**ater Balance **Si**mulation **M**odel) physically based, spatially distributed catchment modelling system. Calibration was completed for this catchment for the period January 1 to December 31, 2004. Discharge simulations performed for year 2004 are shown in Figure 47.

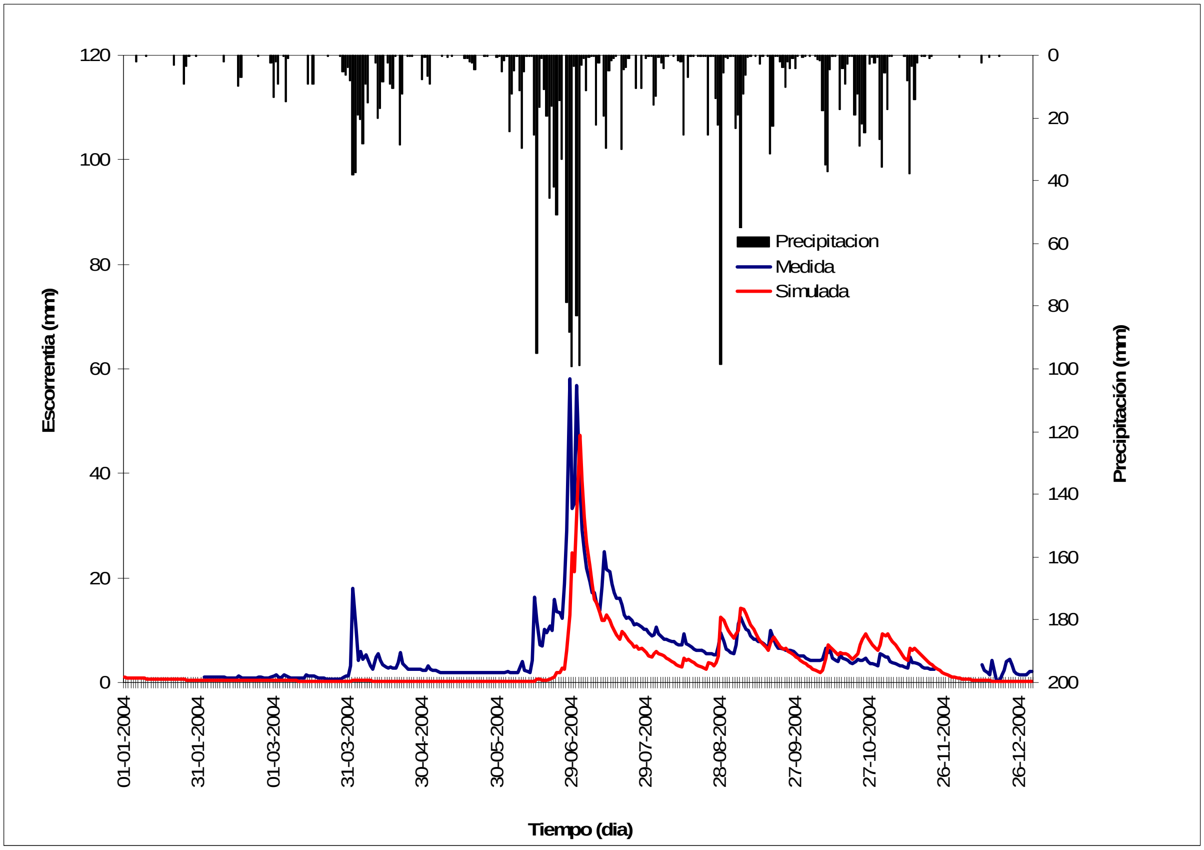


Figure 47. Discharge simulation at Los Ulmos1 experimental catchment using WaSIM.

According to the results obtained in this simulation for year 2004, a coefficient of determination (r^2) of 0.57 was obtained comparing the measured and simulated values. This value is something smaller than the obtained by authors such as Verbunt *et al.* (2003) and Gurtz *et al.*(2003), that obtained determination coefficients surpassing 0.8 simulating runoff in mountain river basins. On the other hand, in a four years simulation Rode and Lindenschmidt (2000) obtained a coefficient of 0.68 that was considered as a good result although the simulation presented a tendency to overestimate the peak.

Something similar tends to happen in this investigation, where the simulated peak values are under or overestimated in relation to the observed records, but the tendency of the graphs is similar (see Figure 47).

According to Rode and Lindenschmidt (2000), in zones of humid climate two mechanisms exist that originate the run-off. The first one occurs when the soil surface is saturated by the precipitations and the second happens when the ground water level rises and the soil is saturated from below. These mechanisms tend to happen in zones near to the drainage network. In humid climates the precipitation, soil saturation and the presence or absence of interflow will accelerate or slow down the generation of overland flow.

Some investigators have raised the necessity to consider the initial characteristics of the soil and the precipitations, to be able to carry out a successful simulation (Niehoff *et al*. 2002, Piepho 2002 and Verbunt *et al.* 2003). Thus, the quality of the simulation will be in direct relation with the quality of the input data and the calibrated parameters.

5. CONCLUSIONS

The data presented in this report provides an insight to the basin response associated to plantation forestry development in Chile. Different studies have been carried out in diverse research sites and forest cover conditions and add significantly to the knowledge of the hydrological behavior of forested small and large catchments in the country.

In small experimental catchments, the reduction of vegetation cover generates increases in annual and summer runoff and peak discharges, and the biggest effects happen after clearfelling significant proportions of a forest within the catchments. The combined effect of rainfall pattern, catchment size and topography, road density and extent of affected area should also be considered to fully understand and explain the hydrological effects of land use changes in these catchments.

Following clearcutting of the *Pinus radiata* plantation that covered the 79.4% of the La Reina experimental catchment, runoff and peak flows increase both at annual and summer levels. During the first three years of the post-harvesting period, on average a 110% increase in annual runoff occurred and mean peak flows were 32% higher. In the wet temperate region with high annual rainfall totals concentrated during winter months as the one where the La Reina catchment is located, timber harvesting has a greater effect in increasing annual runoff than peak flows. After 6 years of development of the new *Eucalyptus spp*. plantation established in the La Reina catchment in 2000, this forest is increasingly consuming water and annual runoff has initiated a recovery towards pre-harvesting levels.

In the two Los Ulmos experimental catchments, the older plantation in Los Ulmos1 increasingly consumed more water than the three years younger forest cover established at Los Ulmos2 (59 mm in 2000 and 217 mm in 2002), although mean specific peak flows differences between these catchments were not significant. Data from La Reina, Los Ulmos1 and Los Ulmos2 show a decrease in the annual runoff (in percentage of annual precipitation) as the plantations increase their water consumption capacities from about 68% the year after timber harvesting to 36% after 22 years of plantation growth. Reductions of forest cover appear to cause higher runoff and peak flows, although catchment morphology, extent of data sets and rainfall characteristics occurred before and after forest operations should be carefully considered to fully understand the hydrological effects of forest cover changes.

Comparisons of peak flows at the La Reina catchment for pre and post-harvesting conditions indicate that the percentage change for the ‘large’ event category (events with rainfall volumes greater than 50 mm) is less than that resulting from both the ‘medium’ (from 10 to 50 mm) and ‘small’ (from 5 to 10 mm) event size categories as was hypothesized. Nevertheless, peak flow medians for 2006 are still higher than those from the pre-harvesting conditions indicating that peak flow values after the removal of the plantation do not show an initial important increase followed of a gradual diminution tending towards the peak discharge levels of the pre-harvesting condition. Although runoff in La Reina has initiated in 2006 a decrease tending towards the levels of the pre-harvesting condition, this is not yet the case of the peak flows.

At the La Reina catchment peak flow values from pre and post-harvesting land cover conditions only differ for events with less than 10-year return periods. The relationship between extreme rainfall events exceeding 100 mm in total precipitation (the upper section of the ‘Large’ event size category) and extrapolation of this relationship to increasingly larger rainfall event sizes does appear to suggest that at the scale of extreme events peak flow values with return periods exceeding 10 years do not differ considerably for pre and post-harvesting land cover conditions. This result appears consistent with the suppositions regarding peak flows and extreme events.

In large catchments, annual water reductions associated to the increase in forested area have been detected. A reduction of 157 to 440 mm/year in runoff was identified in three large river basins. In two of these basins the reduction in annual runoff can be explained through the increase of annual evapotranspiration capacity of the new planted area, whereas in the third basin annual runoff reductions are controlled not only by increases in forest water consumption. In the three river basins, the values of $Q_{50\%}$, $Q_{80\%}$ and $Q_{90\%}$ of the summer months are lower since 1979 (the year since reductions in runoff were detected). In the three river basins the highest reduction occurs for $Q_{50\%}$. The values of $Q_{50\%}$, represent periods during the summer with a certain soil water availability, which as of year 1979 is being consumed by the forests covering an important part of the area of these river basins. The values of $Q_{80\%}$ and $Q_{90\%}$ represent periods during the summer with lower soil water availability in which the physiological activity of the trees is noticeably reduced, and this could be the reason why the effect of the increase of the afforested area on these low flows seems to be smaller. Since $Q_{80\%}$ and $Q_{90\%}$ are used to define permanent and continuous Water Rights, it is possible that already existing permanent and continuous water rights could be only marginally being affected by the increase of the planted area. However, those eventual water rights, more associated to $Q_{50\%}$, would be the most possible affected.

At the Caramávida and Duqueco river basins, for a same return period the daily maximum discharges from the “after year 1979” period are superiors that the corresponding ones to “before year 1978”, which could indicate that the development of the plantations in these river basins, that generated a reduction in water production, does not reduce the levels of peak discharges. Although, in the Mulchén river basin, the daily maximum discharges are smaller in the period of forest development, indicating in this case a potential effect of afforestation in decreasing both water yield and peak flows. To the effect of the increase of the afforested area it is necessary to add the corresponding to the variations from one period to the other in the intensity pattern of the precipitations that generate these peak flows, and because rainfall is not uniform over a large area even during large storms, differences in areal distribution of precipitation among storms and study periods can add to the variability of peak flows when comparing the periods “before year 1978” with “after year 1979”.

For each of the Caramávida, Duqueco and Mulchén river basins several pair of storms (one storm from the pre-plantation development period and one from the post-plantation development period) were identified and chosen in terms of similar total event precipitation and accumulated rainfall for the previous 7 and/or 14 days. The trends of the relationships between these rainfall events and the resultant peak discharge values for the three river basins and extrapolations of the relationships to increasingly larger rainfall event sizes do appear to suggest that at the scale of extreme events, the corresponding peak flow values from pre and post-plantation development land cover conditions do not differ considerably. In these three river basins, the differences in peak flow values from pre and post-plantation development conditions only differ for events with return periods lower than 5 years. These results appear consistent with the suppositions regarding peak flows and extreme events and the findings for the smaller experimental catchments.

In small experimental catchments, the increases in sediment load after clearfelling can be defined as extreme events not generated by intense rainfalls but associated to plantation forest operations. This reinforces the proposals that the EPIC-UACh group, within the framework of best management practices and definition of standards for harvesting and road planning, has been raising in forums and discussion groups

The results presented in this document can be used to provide recommendations regarding forest management options, which allow adequate tree growth rates but are compatible with restrictions on water availability.

6. REFERENCES

Aboal, J.R., Morales, D., Hernandez, M., Jimenez, M.S. 1999. The measurement and modelling of the variation of stemflow in a laurel forest in Tenerife, Canary Islands. Journal of Hydrology 221: 161-175.

Andréassian, V. 2004. Water and forests: from historical controversy to scientific debate. Journal of Hydrology 291: 1-27.

Aussenac, G. 1969. Influences du couvert forestier sur les précipitations. Revue Forestière Francaise 7: 631-635.

Aussenac, G. 1981. Influence du Hêtre sur le cycle de l'eau el sur le microclimat. p. 136-153. In: Le Hêtre. INRA, Département des Recherches Forestiéres, Paris, France, 613 p.

Aussenac, G., Boulongeat, C. 1980. Interception des précipitations et évapotranspiration rèelle dans des peuplements de feuillu (Fagus silvatica) et de résineux (Pseudotsuga menziesii). Annales des Sciences Forestiéres 37: 91-107.

Bathurst, J.C., Birkinshaw, S.J., Evans, J., Francke, S. 1998. Modelo de bases físicas para la predicción de los impactos hidrológicos y la erosión de los suelos provocados por opciones de la gestión forestal en Chile. Documento Técnico 120, Chile Forestal, Octubre 1998, 8 p.

Bari, M.A., Smith, N., Ruprecht, J.K., Boyd, B.W. 1996. Changes in streamflow components following logging and regeneration in the southern forest of Western Australia. Hydrological Processes 10 (3): 447-461.

Beasley, R.S., Granillo, A.B. 1988. Sediment and water yields from managed forests on flat coastal plain soils. Water Resources Bulletin 24(2): 361-366.

Beschta, R.L., Pyles, M.R., Skaugset, A.E., Surfleet, C.G. 2000. Peak flow responses to forest practices in the western cascades of Oregon, USA. Journal of Hydrology 233: 102-120.

Binkley, D., Brown, T.C. 1993. Forest practices as nonpoint sources of pollution in North America. Water Resources Bulletin 29(5): 729-740.

Birkinshaw, S.J., Bathurst, J.C. 2007. Model Analysis of Land-use Impact on Flood Response for the EPIC FORCE Focus Areas. Deliverable 14, INCO-CT2004-510739, Evidence-based Policy for Integrated Control of Forested River Catchments in Extreme Rainfall and Snowmelt (EPIC FORCE), University of Newcastle upon Tyne, 71 p.

Brown, T.C., Binkley, D. 1994. Effect of management on water quality in North American forests. General Technical Report RM-248. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experimental Station. 27p.

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R.A. 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310: 28-61.

Buttafuoco, G., Callegari, G., Cinnirella, S., Iovino, F. 1994. Hydrological balance and erosion observations on oak coppices. In Proc. of the International Symposium on Forest Hydrology, Tokyo, Japan. pp. 585-591.

Caldentey, J., Fuentes, J. 1995. Niederschlagsverteilung in drei Waldbeständen der Gebirgskette Nahuelbuta, Chile. Sonderdruck aus Wetter und Leben, 47, Jahrgang, Heft 2-4/95:129-140.

Calder, I.R. 1992. The hydrological impact of land-use change. In Proceedings of the Conference on Priorities for Water Resources Allocation and Management, Natural Resources and Engineer Advisers Conference, Southampton, July 1992. Overseas Development Administration, 91-101.

Cameron, J. 2003. Victorian plantations and catchment water yield. Plantation Timber Association of Australia, Australian Paper Industry Council, Australian Forest Growers. PTAA Report No3. 32 p.

Cassie, D., Jolicoeur, S., Bouchard, M., Poncet, E. 2002. Comparison of streamflow between pre and post timber harvesting in Catamaran Brook (Canada). Journal of Hydrology 258: 232-248.

CONAF-CONAMA. 1999. Catastro y evaluación de recursos vegetacionales nativos de Chile, Informe Nacional con Variables Ambientales. Proyecto CONAF-CONAMA-BIRF, Santiago, Chile, 88 p.

CORMA. 2006. Charla: desarrollo sustentable sector forestal. En: www.cormabiobio.cl/6accionar/bibliotecas/documentos/desarrollosust.ppt

CORMA. 2007. RECURSO FORESTAL / Plantaciones Forestales. INTERNET: http://www.corma.cl/portal/menu/recurso_forestal/Plantaciones. January 12, 2007.

Cornet, A. 1977. Etude comparative du bilan hydrique d'une parcelle boisée et d'une parcelle herbeuse a Madacascar. Revue Bois et Forêts des Tropiques 176: 3-11.

Cornish, P.M. 1993. The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. Journal of Hydrology 150: 301-322.

Crockford, R.H., Richardson, D.P. 1990a. Partitioning of rainfall in a Eucalypt forest and Pine plantation in southeastern Australia: I Throughfall measurement in a Eucalypt forest: effect of method and species composition. Hydrological Processes 4: 131-144.

Crockford, R.H., Richardson, D.P. 1990b. Partitioning of rainfall in a Eucalypt forest and Pine plantation in southeastern Australia: II Stemflow and factors affecting stemflow in a dry sclerophyll Eucalypt forest and a Pinus radiata plantation. Hydrological Processes 4: 145-155.

Crockford, R.H., Richardson, D.P. 1990c. Partitioning of rainfall in a Eucalypt forest and Pine plantation in southeastern Australia: III Determination of the canopy storage capacity of a dry sclerophyll Eucalypt forest. Hydrological Processes 4: 157-167.

Crockford, R.H., Richardson, D.P. 1990d. Partitioning of rainfall in a Eucalypt forest and Pine plantation in southeastern Australia: IV The relationship of interception and canopy storage capacity, the interception of these forests, and the effect on interception of thinning the Pine plantation. Hydrological Processes 4: 169-188.

Crockford, R.H., Richardson, D.P. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrological Processes 14: 2903-2920.

Cronan, C.S., Reiners, W.A. 1983. Canopy Processing of Acid Precipitation by Coniferous and Hardwood Forests in New England. Oecologia 59: 316-323.

David, J.S., Henriques, M.O., David, T.S., Tomé, J., Ledger, D.C. 1994. Clearcutting effects on streamflow in coppiced Eucalyptus globulus stands in Portugal. Journal of Hydrology 162: 143-154.

Davie, T.J.A., Durocher, M.G. 1997a. A model to consider the spatial variability of rainfall partitioning within deciduous canopy. I. Model description. Hydrological Processes 11: 1509-1523.

Davie, T.J.A., Durocher, M.G. 1997b. A model to consider the spatial variability of rainfall partitioning within deciduous canopy. II. Model parameterization and testing. Hydrological Processes 11: 1525-1540.

Denison, W.C. 1973. Life in tall trees. Scientific American 288: 74-80.

Dye, P.J. 2000. Water use efficiency in South African Eucalyptus `plantations: A review. Southern African Forestry Review 189: 17-26.

Dye, P.J., Poulter, A.G. 1995. A field demonstration of the effect on streamflow of clearing invasive pine and wattle trees from a riparian zone. South African Forestry Journal 173: 27-30.

DWAF. 1996. Sustainable forest development in South Africa: the policy of the Government of National Unity. White paper, Department of Water Affairs and Forestry, Pretoria, South Africa.

http://www-dwaf.pwv.gov.za/Forestry/Forestry%20Policy/whitepap.html.

Edmonds, R.L., Thomas, T.B., Rhodes, J.J. 1991. Canopy and soil modification of precipitation chemistry in a temperate rain forest. Soil Science Society of America Journal 55: 1685-1693.

Edmonds, R L., Blew, R.D. 1997. Trends in precipitation and stream chemistry in a pristine old-growth forest catchment, Olympic National Park, Washington. Journal of the American Water Resources Association 33 (4): 781-793.

Ensign, S.H., Mallin, M.A. 2001. Stream water quality changes following timber harvest in a coastal plain swamp forest. Water Research 35(14): 3381-3390.

FAO. 2000. The global outlook for future wood supply from forest plantations. Global Forest Products Outlook Study. Working Paper Series, Working Paper No: GFPOS/WP/03. http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/003/X8423E/X8423E00.htm

Fahey, B. 1994. The effect of plantation forestry on water yield in New Zealand. New Zealand Journal of Forestry 39(3): 18-23.

FSC. 2007. FSC certified forests. http://www.fsc.org/en/whats_new/fsc_certificates.

Galloway, J.N., Levy, H., Kasibhatala, P.S. 1994. Year 2020: Consequences of population growth and development on deposition of oxidised nitrogen. Ambio 23: 120-123.

Galloway, J.N., Keene, W.C., Likens, G.E. 1996. Processes of controlling the composition of precipitation at a remote Southern Hemispheric location: Torres del Paine National Park, Chile. Journal of Geophysical Research 101(3): 6883-6897.

Gash, J.H.C., Lloyd, C.R., Lachaud, G. 1995. Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology 170: 79-86.

Gayoso, J., Iroumé, A. 1984. Soil disturbance from logging in southern Chile. In Proceedings of the Symposium on Effects of Forest Land Use on Erosion and Slope Stability, Honolulu, Hawaii, O'Loughlin, C.L., Pearce, A.J. (eds). Environment and Policy Institutes, East-West Center, Honolulu, Hawaii, 203-209.

Gayoso, J., Iroumé, A. 1991a. Compaction and soil disturbances from logging in southern Chile. Annales des Sciences Forestiéres 48(1):63-71.

Gayoso, J., Iroumé, A. 1991b. Metodología para estimar la fragilidad en terrenos forestales. Medio Ambiente 11(2):13-24.

Gayoso, J., Iroumé, A. 1995. Impacto del manejo de plantaciones sobre el ambiente físico. Bosque 16 (2):34-56.

Godoy, R., Oyarzún, C., Bahamondes, J. 1999. Hydrochemical fluxes in a Nothofagus pumilio forest in Puyehue National Park, southern Chile. Revista Chilena de Historia Natural 72: 579-594.

Godoy, R., Oyarzun, C., Gerding, V. 2001. Precipitation chemistry in deciduous and evergreen Nothofagus forest of southern Chile under a low-deposition climate. Basic and Applied Ecology 2: 65-72.

Gross, P., Hajek, E. 1998. Indicadores de calidad y gestión ambientales. Ed. Alfabeta. Santiago de Chile. 211 p.

Gurtz, J.; Zappa, M.; Jasper, K.; Lang, H.; Verbunt, M.; Badoux, A. y Vitvar, T. 2003. A comparative study in modelling runoff and its components in two mountainous catchments. Hydrological Processes 17, 297-311.

Gush, M.B., Scott, D.F., Jewitt, G.P.W., Schulze, R.E., Hallowes, L.A., Gorgens, A.H.M. 2002. A new approach to modelling streamflow reductions resulting from commercial afforestation in South Africa. Southern African Forestry Journal 196: 27-36.

Harr, R. 1976. Forest practices and streamflow in western Oregon. US Dep. Agric., For. Serv., Gen. Tech. Rep. PNW-49. 18p.

Harr, R., Fredriksen, R.L., Rothacher, J. 1979. Changes in streamflow following timber harvest in southwestern Oregon. USDA For. Serv., Gen. Tech. Rep. PNW-249. 22 p.

Haydon, E.R., Benyon, R.G., Lewis, R. 1996. Variation in sapwood area and throughfall with forest age in mountain ash (Eucalyptus regnans F. Muell.). Journal of Hydrology 187: 351-366.

Hedin, O.L., Campos, H. 1991. Importance of small streams in understanding and comparing catchment ecosystem processes. Revista Chilena de Historia Natural 64: 583-596.

Hedin, O.L., Armesto, J.J., Johnson, A.H. 1995. Patterns of nutrient loss from unpolluted, old-growth temperate forests: evaluation of biogeochemical theory. Ecology 76(2): 493-509.

Helvey, J.D. 1980. Effect of a north-central Washington wild-fire on runoff and sediment production. Water Resources Bulletin 16(4): 625-634.

Hibbert, A.R. 1967. Forest treatment effects on water yield. In: Sopper, W.E., Lull, H.W. (Eds.). Symposium of Forest Hydrology. Pergamon Press, New York, pp. 527-543.

Hofstede, R., Lips, J., Jongsma, W., Sevink, J. 1998. Geografía, ecología y forestación de la sierra Alta del Ecuador. Ed. Abya Yala, Ecuador. 242 p.

Howard, O. 1972. Throughfall and stemflow relationship in second growth Ponderosa pine in the Black Hills. USDA Forest Service, Research Note. U.S. Department of Agriculture, Forest Service. U.S.A. 7 p.

Huber, A. 1990. Variaciones anuales en precipitación, escurrimiento fustal e intercepción en un bosque adulto de Pinus radiata (D. Don). Turrialba 40(4): 503-508.

Huber, A., Iroumé, A. 2001. Variability of annual rainfall partitioning for different sites and forest covers in Chile. Journal of Hydrology 248: 78-92.

Huber, A., López, D. 1993. Cambios en el balance hídrico provocados por tala rasa de un rodal de Pinus radiata (D. Don), Valdivia, Chile. Bosque 14 (2):11-18.

Huber, A., Martínez, A. 1995. Redistribución de las precipitaciones en un bosque de la pluviselva Valdiviana. Medio Ambiente 12 (2): 7-13.

Huber, A., Oyarzún, E. 1983. Precipitación neta e intercepción en un bosque adulto de Pinus radiata (D. Don). Bosque 5 (1): 13-21.

Huber, A., Oyarzún, E. 1990. Variaciones anuales en precipitación, escurrimiento e intercepción en un bosque adulto de Pinus radiata. Turrialba 40 (4): 503-508.

Huber, A., Oyarzún, C. 1992. Redistribución de las precipitaciones en un bosque siempreverde del sur de Chile. Turrialba 42(2): 192-194.

Huber, A., Oyarzún, C., Vasquez, S. 1985. Balance hídrico en tres plantaciones de Pinus radiata (D.Don). I: Redistribución de las precipitaciones. Bosque 6: 3-14.

Huber, A., Iroumé, A., Bathurst, J.C. 2007. Effect of Pinus radiata plantations on water balance in Chile. Hydrological Processes (en prensa).

INFOR. 2005. El Sector forestal Chileno, una mirada. Ministerio de Agricultura. 68 p.

Iovino, F., Cinnirella, S., Veltri, A., Callegari, G. 1998. Processus hydriques dans des écosystèmes forestiers. Ecologie 29: 369-375.

Iroumé, A. 1990. Assessment of runoff and suspended sediment yield in a partially forested catchment in southern Chile. Water Resources Research 26(11):2637-2642.

Iroumé, A. 1992. Precipitación, escorrentía y producción de sedimentos en suspensión en una cuenca cercana a Valdivia, Chile. Bosque 13(2):15-23.

Iroumé, A. 1997. Estudio de los procesos hidrológicos en una cuenca experimental forestal andina de la IX región, Chile. Bosque 18(1): 73-81.

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 (1): 125-135.

Iroumé, A., Huber, A. 2000. Intercepción de las lluvias por la cubierta de bosques y efecto en los caudales de crecida en una cuenca experimental en Malalcahuello, IX Región, Chile. Bosque 21(1): 45-56.

Iroumé, A., Huber, A. 2002. Comparison of interception losses in a broadleaved native forest and a Pseudotsuga menziesii plantation in the Andes Mountains of southern Chile. Hydrological Processes 16(12): 2347-2361.

Iroumé, A., Gayoso, J., Infante, L. 1989. Erosión hídrica y alteración del sitio en cosecha a tala rasa. Revue d'Ecologie et de Biologie du Sol 26(2): 171-180.

Iroumé, A., Schuller, P., Mancilla, H.B., Castillo, A., Trumper, R.E. 2004. Applicability of the 7Be technique to estimate soil redistribution rates associated to recent forest harvest operations in the Lake Region, Chile. 8th Biannual Meeting 2004, South Pacific Environmental Radioactivity Association, Valdivia, Chile, 11-15 October 2004.

Iroumé, A., Huber, A., Schulz, K. 2005. Summer flows in experimental catchments with different forest covers, Chile. Journal of Hydrology 300 (1-4): 300-313.

Iroumé, A., Mayén, O., Huber, A. 2006. Runoff and peak flow responses to timber harvest and forest age in Southern Chile. Hydrological Processes (in press).

IUFRO. 2005. IUFRO NEWS, volume 34, issue 1/2005, page 2. http://www.iufro.org/fileadmin/material/publications/news-noticias/news05-1.pdf

Jackson, N.A. 2000. Measured and modelled rainfall interception loss from an agroforestry system in Kenya. Agricultural and Forest Meteorology 100: 323-336.

Jones, J.A. 2000. Hydrological processes and peak discharge response to forest removal, regrowth, and roads in ten small experimental basins, western Cascades, Oregon. Water Resources Research 36 (9): 2621-2642.

Jones, J.A., Grant, G.E. 1996. Peak flow response to clearcutting and roads in small and large basins, western Cascades, Oregon. Water Resources Research 32 (4): 959-974.

Jones, J.A., Swanson, F.J. 2001. Hydrological inferences from comparisons among small basin experiments. Hydrological Processes 15: 2363-2366.

Keenan, R.J., Kimmins, J.P. 1993. The ecological effects of clear-cutting. Environ. Rev., 1:121-144.

Kelliher, F., Whitehead, D., Pollock, D.S. 1992. Rainfall interception by trees and slash in a young Pinus radiata (D. Don) stand. Journal of Hydrology, 131 (1): 187-204.

Keppeler, E.T. 1986. The effects of selective logging on low flows and water yield in a Coastal stream in northern California. M.Sc. Thesis. Humboldt State University, Arcata. 137p.

Keppeler, E.T. 1998. The summer flow and water yield response to timber harvest. USDA For. Serv., Gen. Tech. Rep. PSW-168, pp.35-43.

Keppeler, E.T., Ziemer, R.R. 1990. Logging effects on streamflow: water yield and summer low flows at Caspar Creek in north-western California. Water Resources Research 26 (7): 1669-1679.

La Marche, J.L., Lettenmaier, D.P. 2001. Effects of forest roads on flood flows in the Deschutes river, Washington. Earth Surface Processes and Landforms 26: 115-134.

Lane, P.N.J., Mackay, S.M. 2001. Streamflow response of mixed-species eucalypt forests to patch cutting and thinning treatments. Forest Ecology and Management 143: 131-142.

Lankreijer, H.J.M., Hendriks, M.J., Klaassen, W. 1993. A comparison of models simulating rainfall interception of forests. Agricultural and Forest Meteorology 64: 187-199.

Lankreijer H.J.M, Lundberg, A., Grelle, A., Lindroth, A., Seibert, J. 1999. Evaporation and storage of intercepted rain analysed by comparing two models applied to a boreal forest. Agricultural and Forest Meteorology 98-99: 595-604.

Lenzi, M.A., Iroumé, A., Mao, L., Palacios, H. 2004. Analysis of Sediment Transport in Experimental Alpine and Andean Catchments. Proceedings 10° International Symposium Interpraevent 2004, Riva del Garda, Tn, Italy, 24-28 May 2004, II, 77-88.

Likens, G.E., Keene, W.C., Miller, J.M., Galloway, J.N. 1987. Chemistry of precipitation from a remote, terrestrial site in Australia. Journal of Geophysical Research 92: 13299-13314.

Loustau, D., Berbigier, P., Granier, A. 1992. Interception loss, throughfall and stemflow in a maritime pine stand. II: An application of Gash's analytical model of interception. Journal of Hydrology 138: 469-485.

Lund, H.G., Iremonger, S. 2000. Omissions, commissions, and decisions: the need for integrated resource assessments. Forest Ecology and Management 128: 3-10.

MacDonald, L.H., Stednick, J.D. 2003. Forests and Water: A State-of-the-Art Review for Colorado. Colorado State University. CWRRI Completion Report No.196. 65 p.

Mayén, O. 2003. Respuesta del cambio de cobertura vegetacional en los caudales estacionales, caudales máximos y en el transporte de sedimentos en cuencas experimentales de la X[a] Región. Tesis, Magíster en Ciencias mención Recursos Forestales. Valdivia, Universidad Austral de Chile, Fac. Cs. Forestales. 103 p.

McMinn, J.W. 1984. Soil disturbance by fuelwood harvesting with a conventional ground system and a cable miniyarder in mountain hardwood stands. P. 93-98. In: Peters, PA., Luchok, J., eds., Proceedings from Mountain Logging Symposium. Charleston, WY: West Virginia University.

National Council for Air and Stream Improvement. 1994. Forests as nonpoint sources of pollution, and effectiveness of best management practices. Tech. Bull N°672. New York, NY: National Council for Air and Stream Improvement.

Neal, C., Robson, A.J., Hall, R.L., Ryland, G., Conway, T., Neal, M. 1991. Hydrological impacts of hardwood plantation in lowland Britain: preliminary findings on interception at a forest edge, Black Wood, Hampshire, southern England. Journal of Hydrology 127: 349-365.

Neal, C., Robson, A.J., Bhardwaj, C.L., Conway, T., Jeffery, H.A., Neal, M., Ryland, G.P., Smith, C.J., Walls, J. 1993. Relations between precipitation, stemflow and throughfall for a lowland beech plantation, Black Wood, Hampshire, southern England: findings on interception at a forest edge and the effects of storm damage. Journal of Hydrology 146 (1): 221-233.

Niehoff, D.; Fritsch, U.; Bronstert, A. 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. Journal of Hydrology 267, 80-93.

Olivares, G. 2003. Caracterización de los procesos de transporte de sedimentos entre una cuenca andina (IX Región) y una cuenca de la Cordillera de la Costa (X Región). Trabajo de Titulación Ing. Forestal. Valdivia. Universidad Austral de Chile, Fac. Cs. Forestales. 47 p.

Oyarzún, C., Godoy, R., Sepúlveda, A. 1998. Water and nutrient fluxes in a cool temperate rainforest at the Cordillera de la Costa in southern Chile. Hydrological Processes 12: 1067-1078.

Patric, J.H. 1978. Harvesting effects on soils and water in the eastern hardwood forest. Southern Journal of Applied Forestry 2(3): 66-73.

Piepho, B. 2002. Evaluation of the hydrological behavior in a small catchment by using the model WaSiM. A case study within the IPMS-Project in Nepal. Landschaftsökologe und Umweltforschung 38, 142-155.

Pizarro R, Araya S, Jordán C, Farías C, Flores JP, Bro PB. 2006. The effect of changes in vegetation cover on river flows in the Purapel river basin of central Chile. Journal of Hydrology 327: 249-257.

Pook, E.W., Moore, P.H.R., Hall, T. 1991. Rainfall interception by trees of Pinus radiata and Eucalyptus viminalis in a 1300 mm rainfall area of southeastern New South Wales: II. Influence of wind-borne precipitation. Hydrological Processes 5: 143-155.

Price, N. 1982. A comparison of water balance components in natural and plantation forests in El Salvador, Central America. Turrialba 32 (4): 399-416.

Primrose, H. 2004. Peak flow and suspended sediment responses to plantation harvesting in The La Reina catchment, southern Chile. Thesis, MSc Sustainable Management of the Water Environment. School of Civil Engineering and Geosciences, University of Newcastle upon Tyne.

Potter, C.S., Ragsdale, H L., Swank, W.T. 1991. Atmospheric deposition and foliar leaching in a regenerating southern appalachian forest canopy. Journal of Ecology 79: 97-115.

Rapp, M. 1969. Apport des éléments minéraux au sol par les eaux de pluviolessivage sous des peuplements de Quercus ilex L., Quercus lanuginosa Lamk. et Pinus Halapensis Mill. Oecologia 4: 71-92.

Rivas, J. 2000. Erosión hídrica y parámetros físico-químico del escurrimiento superficial en plantaciones forestales. Tesis Ing. For. Valdivia. Universidad Austral de Chile, Fac. de Cs. Forestales. 85 p.

Rode, M.; Lindenschmidt, K. 2001. Distributed sediment and Phosporus transport modeling on a medium sized catchment in Central Germany. Phys. Chem. Earth (B) 26 (7-8), 635-640.

Romero, H. 1985. Geografía de los Climas. Colección Geografía de los Climas. Instituto Geográfico Militar. Santiago, Chile. 240p.

Rothacher, J. 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. Water Resources Research 6: 653-658

Rowe, L.K., Pearce, A.J. 1994a. Hydrology and related changes after harvesting native forest catchments and establishing Pinus radiata plantations. Part 1. Introduction to study. Hydrological Processes 8: 263-279.

Rowe, L.K., Pearce, A.J. 1994b. Hydrology and related changes after harvesting native forest catchments and establishing Pinus radiata plantations. Part 2. The native forest water balance and changes in streamflow after harvesting. Hydrological Processes 8: 281-297.

Rowe, L.K., Taylor, C.H. 1994. Hydrology and related changes after harvesting native forest catchments and establishing Pinus radiata plantations. Part 3. Stream temperatures. Hydrological Processes 8: 299-310.

Ruprecht, J.K., Schofield, N.J., Crombie, D.S., Vertessy, R.A., Stoneman, G.L. 1991. Early hydrological response to intense forest thinning in southwestern Australia. Journal of Hydrology 127: 261-277.

Ruprecht, J.K., Stoneman, G.L. 1993. Water yield issues in the jarrah forest of south-western Australia. Journal of Hydrology 150: 369-391.

Rutter, A.J., Kershaw, K.A., Robins, P.C., Morton, J. 1971/1972. A predictive model of rainfall interception in forests, I. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology 9: 367-384.

Rutter, A.J., Morton, A.J., Robins, P.C. 1975. A predictive model of rainfall interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwood stands. Journal Applied Ecology 12: 367-380.

Rutter, A.J., Morton, A.J. 1977. A predictive model of rainfall interception in forests. III. Sensitivity of the model to stand parameters and meteorological variables. Journal Applied Ecology 14: 567-588.

Schellekens, J., Scatena, F.N., Bruijnzeel, L.A., Wickel, A.J. 1999. Modelling rainfall interception by a lowland tropical rain forest in northeastern Puerto Rico. Journal of Hydrology 225: 168-184.

Schuller, P., Iroumé, A., Mancilla, H.B., Trumper, R.E., Castillo, A. 2004. Applicability of the 7Be technique to estimate soil redistribution rates associated to recent forest harvest operations in the Lake Region of Chile. Second Research Co-ordination Meeting of the Co-ordination Research Project "Assess the effectiveness of soil conservation techniques for sustainable watershed management using fallout radionuclides (D1-50.08)", Istanbul, Turkey, 4-9 October 2004.

Schuller, P., Iroumé, A., Walling, D.E., Mancilla, H., Castillo, A., Trumper, R.E. 2006. Use of ^{7}Be to document Soil Redistribution following Forest Harvest Operations. Journal of Environmental Quality 35: 1756-1763.

Smith, P.J.T. 1987. Variation of water yield from catchments under grass and exotic forest, east Otago. Journal of Hydrology (New Zealand) 26: 175-184.

Stednick, J.D. 1996. Monitoring the effects of timber on annual water yield. Journal of Hydrology 176:79-95.

Stolzenbach, C. 1998. Generación de caudales y cuantificación de pérdidas de suelo en suelos rojo arcillosos de la Provincia de Valdivia, X Región. Tesis Ing. Forestal. Valdivia, Universidad Austral de Chile, Facultad de Ciencias Forestales. 84 p.

Stoneman, G.L., Schofield, N.J. 1989. Silviculture for water production in jarrah forest of Western Australia: an evaluation. Forest Ecology and Management 27: 273-293.

Stringer, J., Thompson, A. 2000. Comparison of forestry best management practices, Part I: Streamside management zones. Forest Landowner. May/June 2000: 22-27.

Sutton, W.R.J. 1999. The need for planted forests and the example of radiate pine. New Forests 17: 95-109.

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S.G., Vose, J.M. 2006. Potential water yield reduction due to forestation across China. Journal of Hydrology 328: 548–558.

Swank, W.T., Vose, J.M., Elliot, K.J. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. Forest Ecology and Management 143 (1): 163-178.

Swanson, R.H., Hillman, G.R. 1977. Predicted increased water yield after clear-cutting verified in west-central Alberta. Northern For.Res.Cent.Can.For.Serv., Info.Rep. NOR-X-198. 40p.

Swift, L.W., Swank, W.T. 1981. Long-term responses of streamflow following clearcutting and regrowth. Hydrological Sciences Bulletin 26: 245-256.

Thomas, R.B., Megahan, W.F. 1998. Peak flow response to clear-cutting and roads in small and large basins, western Cascades, Oregon: A second opinion. Water Resources Research 34 (12): 3393-3403.

Tiktak, A. 1994. Soil water dynamics and long-term water balances of a Douglas-fir in the Netherlands. Journal of Hydrology 156(1): 265-283.

Toro, J., Gessel, S. 1999. Radiata pine plantations in Chile. New Forests 18 (1): 33-44.

Troendle, C.A., King, R.M. 1987. The effects of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology 90: 145-157.

Uriarte, A. 1994. Plantaciones en suelos erosionados y sustitución ¿qué superficie?. CORMA 239:35-37.

Uyttendaele, P.G.Y. 2006. Procesos de transporte de sedimentos en áreas de montaña, comparación entre la cuenca del río Cordón (Alpes, Italia) y del estero Tres Arroyos (Andes, Chile). Tesis Doctorado en Ciencias Forestales, Universidad Austral de Chile, programa de co-tutela con Università degli Studi di Padova (Italia).

Uyttendaele, G.P.Y., Iroumé, A. 2002. The solute budget of a forest catchment and solute fluxes within a Pinus radiata and a secondary native forest site, southern Chile. Hydrological Processes 16: 2521-2536.

Valente, F., David, J.S., Gash, J.H.C. 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. Journal of Hydrology 190: 141-162.

Verbunt, M.; Gurtz, J.; Jasper, K.; Lang, H.;Warmerdam, P.; Zappa, M. 2003. The hydrological role of snow and glaciers in alpine river basins and their distributed modeling. Journal of Hydrology 282, 36-55.

Voigt, G. 1960. Distribution of rainfall under forest stands. Forest Science 6 (1):2-10.

Ward, R., Robinson, M. 1989. Principles of Hydrology. Third Edition, McGraw-Hill, London, 365p.

Weathers, K.C., Likens, G.E. 1997. Clouds in southern Chile: an important source of nitrogen to nitrogen limited ecosystems? Environmental Science and Technology 31(1): 210-213.

Whelan, M.J., Anderson, J.M. 1996. Modelling spatial patterns of throughfall and interception loss in a Norway spruce (Picea abies) plantation at the plot scale. Journal of Hydrology 186: 335-354.

Whitehead, P.G., Robinson, M. 1993. Experimental basin studies-an international and historical perspective of forest impacts. Journal of Hydrology 145: 217-230.

Wyers, G.P., Duyzer, J.H. 1997. Micrometeorological measurements of the dry deposition flux of sulphate and nitrate aerosols to coniferous forests. Atmospheric Environment 31: 333-343.

Yoho, N.S. 1980. Forest management and sediment production in the South-a review. Southern Journal of Applied Forestry 4: 27-36.

Ziemer, R.R. 1998. Flooding and stormflows. USDA For. Serv., Gen. Tech. Rep. PSW-168, pp.15-24.

Zimmermann, R.C. 1992. Impactos ambientales de las actividades forestales: orientación para su evaluación en los países en desarrollo. FAO Guía para la Conservación N° 7. Organización de las Naciones Unidas para la Agricultura y la Alimentación. Roma. 80p.

Zhang, L., Dawes, W.R., Walker, G.R. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 14 (3): 701-708.