D I S S E R T A T I O N

Hydrological and Sediment Transport Processes in
Forest Plantations in Southern Chile

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Hydrological and Sediment Transport Processes in Forest Plantations in Southern Chile

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by

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1. **INTRODUCTION**

1.1. **Plantation forestry requirements**

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years, natural forest resources have declined in a number of countries as forests have being cleared, degraded, or withdrawn from production (particularly in the area of natural forest available for wood supply).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). Because planted forests require a great deal of capital, the winning tree species for these man made forests will have at least the following characteristics: fast growing on a wide range of sites; relatively free of pest and diseases; responsive for genetic improvement and management schemes; and, able to provide wood products for a wide range of end uses (Sutton, 1999).

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 (i.e. wilderness protection, biodiversity conservation and meeting demands for recreation and carbon sequestration). 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 which arises both because the physical terrain of 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 large parts of the remaining available land is more valuable in alternative uses such as agriculture, urban development or industry.
Finally, the hydrological effects of large scale afforestation and deforestation and water allocation issues could constrain additional 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 metres 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 onetenth the volume used in irrigated agriculture. The water consumed is a cost required to support the forestry sector as a contributor to our economy."

The study of forest-water related issues will be required in order to provide recommendations regarding forest management options, which could allow adequate tree growth rates but are compatible with restrictions on water availability, both in quantity and quality.

1.2. Plantation forestry in Chile

In Chile, the forest sector participates with the 3.6% of the national GDP and the 12.5% of total exports (INFOR, 2003). Chile and New Zealand share a common origin of part of their indigenous forests which are a relict of the ancient southern hemisphere forests and are composed by a great number of endemic flora species (Salmon, 1980; Marticorena and Rodriguez, 1995). In both countries, plantation forestry based on introduced Monterey pine is very important for their economy (INFOR, 2003; New Zealand Forest Owners Association, 2003). Pinus radiata D.Don (Monterey pine) and Pseudotsuga menziesii (Mirb.) Franco
(Douglas-fir) have been introduced from North America to Chile, New Zealand, South Africa and Australia while *Eucalyptus* spp. have been also introduced from Australia to Chile, New Zealand and South Africa, where they are all managed as production forests under similar management schemes.

Near the 95% 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 300,000 ha at the beginning of the 1970s to 2,100,000 hectares in 2002 and are established with exotic fast growing species formed by evenaged stands where *Pinus radiata* (Monterey pine) and *Eucalyptus* spp. represent the 75 and 17%, respectively, of these man made forests (CORMA, 2003).

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, 2003), and the existing 4.5 million hectares of potentially productive native forests (CONAF-CONAMA, 1999).

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).
1.3. Hydrological consequences of intensive forest operations

The hydrological consequences of intensive forest operations on water yield and quality have received much attention. 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).


Aside from water budgets less is known about canopy interception effects on other catchment hydrological processes. A case in this sense is the stochastic model used to study the rainfall intensity smoothing effect of interception and to extrapolate measured rainfall and throughfall to throughfall expected during extreme events (Keim et al., 2004).
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) and Swank et al. (2001) showed that after timber harvesting -and even after intense thinning- annual streamflow increases significantly 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; Jones and Swanson, 2001; Cassie et al., 2002; Gush et al., 2002), 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 (absorption and desorption) (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 exposes, disturbs and compacts 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 greatly reduce the magnitude of erosion and sedimentation effects (Stringer and Thompson, 2000). The adoption of BMPs can reduce soil losses by up the 50% (Yoho, 1980).
1.4. 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., 2005a).

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). Water yield and sediment delivery at a catchment scale were studied by Iroumé (1990; 1992; 2003), Mayén (2003), Lenzi et al. (2004), Olivares (2003) and Primrose (2004), 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. (2005a, b). 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).

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 2003, about 350,000 and 1.2 million hectares were certified by Forest Stewardship Council and ISO 14001 standards systems, respectively (CORMA, 2003; FSC, 2003). 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. OBJECTIVES OF THE RESEARCH

The main objective of this research is to provide sound information to better understand the hydrological processes associated to the development of plantation forestry in Chile. The studies have been carried out in different forest types in areas with seasonal water deficits, such as the zones with a Mediterranean climate where most of Chile’s commercial forests are located, and they are intended to add to the knowledge of the hydrological effects of plantation forestry in Chile and provide recommendations regarding forest management options, which allow adequate tree growth rates but are compatible with restrictions on water availability.

Figure 1 presents a simplified vision of the global water cycle. In this figure, the processes included in this research are highlighted.

The specific objectives are:

- Quantify and compare canopy interception losses for different forest types and locations on 12-month based periods.
- Quantify and compare canopy interception losses for one research site and two different forest types (a coniferous plantation and a broadleaved native forest) on rainfall event basis.
- Estimate the effects of forest cover on intensity-duration-frequency relationships of rainfall and extreme events with a stochastic model.
- Analyze runoff and peak flow during low-flow periods, comparing water production in pre- and post-harvesting periods and from catchments with different forest covers.
- Compare annual water production and peak flows in pre- and post-harvesting conditions and from catchments with different forest covers.
- Determine the solute budget and stream water quality, compare bulk precipitation chemistry with other sites in Chile, and evaluate net rainfall fluxes (throughfall and stemflow) between a plantation and a native forest stand.
- Analyze erosion and sediment transport rates in forest catchments.

Figure 1. Processes of the water cycle studied in this research (Rainfall redistribution: throughfall, stemflow and interception losses; Stream Flow, Nutrient cycle; and, Sediment cycle).
3. MATERIALS AND METHODS

3.1. Research sites

In Chile, commercial forests are distributed between 34°00’ and 40°40’ latitude south, in areas with Mediterranean influence where annual rainfalls vary from 1000 mm in the north to near 3000 mm in some southernmost sites. 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°00’ and 38°30’ latitude south) and about 3 months in the southern part of the Ninth and up to middle of the Tenth Region (38°30’ to 40°40’ south), Romero (1985).

Results of canopy interception, nutrient fluxes, water production and sediment transport studies come from different research sites and experimental catchments. The location of these sites is presented in Figure 2, which also includes mean annual isohyets.

Table 1 in Huber and Iroumé (2001) lists the canopy interception research sites including location, soil type and long term mean annual precipitation and summarises, for each plot, information about species, density, crown cover, basal area, age of the forest at the beginning of the research and period of data collection. As can be seen, the research sites and experimental plots cover a wide range of native and exotic broadleaved and coniferous species, densities and age of forests.

At the Malalcahuello site, one of the canopy interception sites studied by Huber and Iroumé (2001), a deeper analysis comparing rainfall redistribution processes in a broadleaved native forest and in a coniferous plantation was carried out by Iroumé and Huber (2002). The effect of the characteristics of the vegetation cover on interception losses were analyzed in an area
of the Andes mountains in southern Chile located within the Malalcahuello Forest Reserve, IXth Region, between 71°28’ and 71°35’ west and 38°23’ and 38°30’ south.

Figure 2. Location of research sites and experimental catchments.
Rainfall and throughfall data from the Douglas-fir (*Pseudotsuga menziesii*) stand at the Malalcahuello site presented in Iroumé and Huber (2002), plus additional original information for the same site, was assembled by Keim *et al.* (2004) with data from four Northern American Douglas-fir forests, to investigate with a stochastic model the effects of forest cover on intensity-duration-frequency relationships.

Water production and sediment transport have been studied in five experimental catchments (Iroumé, 1990; 1992; 1997; 2003; Iroumé *et al.*, 2005a, b). The Rio Tres Arroyos catchment (5.93 km²) is located in the Andes Mountains in the Malalcahuello Forest Reserve (38°25.5’-38°27’ S and 71°32.5’-71°35’ W), on sandy soils and with near the 79% of the catchment area covered by broadleaved native forests while the remaining 21% are sandy volcanic ashes above the vegetation limit. The other four experimental catchments (Los Pinos, Los Ulmos1, Los Ulmos2 and La Reina) have between 89.8 and 10.8 ha, are all located on the Coastal Range of mountains on red clayed soils under forest plantation activities. At the Rio Tres Arroyos catchment part of the annual precipitation falls as snow but runoff is dominated by rainfall with low snowmelt participation, while the other experimental catchments have pluvial regimes. Information about soils, aspect, morphometric characteristics, vegetation cover and study periods is presented in Iroumé (1997) and Iroumé *et al.* (2005a, b).

Iroumé *et al.* (2005a) present the results of analysis of runoff in low-flow summer periods in these experimental catchments with different vegetation cover. Iroumé *et al.* (2005b) show the results of a study comparing runoff and peak flows in pre- and post-harvesting periods and for different forest covers.

Rainfall and discharge data from the La Reina experimental catchment presented in Iroumé *et al.* (2005b), plus additional original information from the same catchment, was used by Primrose (2004) to carry out analysis on the differences in peak flow response under both the
pre and post-harvesting conditions. This analysis considered large, medium and small rainfall events, with the supposition that the presence of forest cover may influence the resultant peak flows arising from ‘small’ rainfall events but when larger or extreme events occur, the effects of forest vegetation on peak flows become significantly less important.

Nutrient fluxes were studied by Uyttendaele and Iroumé (2002) at the Los Pinos experimental catchment, with additional facilities to determine rainfall, streamflow, stemflow and throughfall chemistry.

Erosion processes have been studied at the Los Pinos and Los Ulmos catchments. Erosion rates quantified from experimental plots were presented by Iroumé et al. (1989), Stolzenbach (1998) and Rivas (2000). Recent studies comparing erosion rates from experimental plots and those obtained using the 7Be technique are reported by Iroumé et al. (2004) and Schuller et al. (2004).

At the La Reina catchment Mayén (2003) and Primrose (2004) investigated the change in suspended sediment concentration and the annual sediment yield as vegetation develops. Comparisons of sediment data between La Reina and the Rio Tres Arroyos catchments were carried out by Olivares (2003). Transport sediment processes at the Rio Tres Arroyos catchments were analyzed by Iroumé (2003), and then by Lenzi et al. (2004) comparing data from this watershed with an experimental basin in the Alps of northern Italy.

3.2. Experimental equipment

Precipitation was measured at each canopy interception site by at least two automatic rain gauges located near the forest edges.
In every experimental plot, throughfall was measured using one 15-17 cm wide 20-40 m long V-shaped metallic gutter within each forest stand below the canopy connected to a storage tank equipped with a data logger recorder. Stemflow was measured by means of plastic collars around tree stems (10 to 15 tree stems in plantation stands and 20 to 25 trees in native forests) and piped to a storage tank equipped with a float operated automatic data logger recorder (Huber and Iroumé, 2001).

At the Malalcahuello site (Iroumé and Huber, 2002), throughfall was measured using one V-shaped metallic gutter within each experimental plot connected to 150 litre storage tanks equipped with float-operated level recorders linked to data loggers. The gutters had widths of 10.75 and 10.48 cm and lengths of 28.08 and 24.01 m for the native forest and plantation plots, respectively, and with these dimensions the throughfall catchment area was 3.02 m² for the native forest and 2.52 m² for the plantation. The cross sectional area of the storage tanks is 0.159 m² and recorded changes in depth of storage provide fine resolution for throughfall measurements as the ratio between catchment area to storage tank cross sectional area is 19/1 (3.02/0.159) to 16/1 (2.52/0.159). Stemflow was measured using plastic collars around tree stems and piped to additional storage tanks also equipped with automatic level recorders. Eleven trees for the native forest and 12 trees for the Douglas-fir plantation, all representative of the total population, were collared.

Precipitation in each catchment was registered with digital rain gauges. The Rio Tres Arroyos catchment is monitored with 2 raingauges, the Los Pinos and La Reina with one gauge each and at the Los Ulmos area one rain gauge operates halfway from both catchments.

At the Rio Tres Arroyos catchment the water level gauging station corresponds to a natural section equipped with a pressure sensor connected to a continuous data logger (Iroumé, 1997). All the other four experimental catchments are controlled by artificial gauging stations.
equipped with continuous water level data recorders (Uyttendaele and Iroumé, 2002; Iroumé et al. 2005a, b). Sediment transport is manually collected at the Rio Tres Arroyos gauging station during field campaigns to determine suspended sediment concentrations (0.33 l water samples derived from three sub samples obtained at different profile locations within the mainstream) and estimate bed load transport (sampling with a Helley-Smith device), Iroumé (2003). A Global Water WQ700 turbidimeter is also installed at this gauging station although this data has not been further analyzed due to lack of consistent relationship between suspended sediment concentrations and turbidity.

Streamflow samples for suspended sediment concentration are taken at 30 minute intervals by a water pump at the Los Pinos, Los Ulmos 1 and Los Ulmos experimental catchments. Pumping is controlled by the datalogger in such manner that the volume of each streamflow sample is proportional to the instantaneous discharge in order to obtain an integrated representative suspended concentration sample. Sediment transport in these three catchments is completed collecting all sediment trapped in the pond at the gauging stations.

La Reina is equipped with an automatic suspended sediment sampler and a bedload sediment trap located upstream the gauging station.

For the nutrient fluxes study, the equipments at the Los Pinos catchments were reinforced with additional collectors for rainfall, throughfall and stemflow chemistry (Uyttendaele and Iroumé, 2002). Three rain gauges (provided with filters and metallic wire to prevent bird droppings, leaves and other biological material entering the gauges), twelve throughfall collectors (six of them installed along three transects at 5 m intervals in each Pinus radiata and native forest sites) and six stemflow collectors (installed in three trees in each Pinus radiata and native forest sites).
Superficial erosion (sheet erosion) has been measured in experimental plots (usually 10 to 20 m long and 4 m wide with longer side perpendicular to contour lines) installed in areas with different slopes and vegetal covers at the Los Pinos and Los Ulmos catchment sites (Iroumé et al., 1989; Stolzenbach, 1998; Rivas, 2000). Each plot is perimeted by galvanized steel frames to isolate runoff from surrounding area, and overland flow and washed soil moving downslope are collected at the bottom end and piped to a 150 litre storage tank equipped with a float-operated level recorder linked to a data logger. Overland flow is measured continuously and washed soils stored in the tanks is collected weekly or monthly.

At the Los Pinos site, soil redistribution assessed with the $^7$Be technique has been explored to determine soil erosion rates along recently harvested slopes (Iroumé et al., 2004; Schuller et al., 2004). Soils were sampled to determine $^7$Be reference areal activity density and relaxation mass depth, and the resulting erosion rate was compared with the one obtained by direct measurement of the depth of metallic spikes forming a grid along slope transects or from superficial erosion plots.
4. RESULTS AND DISCUSSION

4.1. Rainfall redistribution on 12-month basis

4.1.1. Throughfall, stemflow and interception on 12-month basis

Table 2 in Huber and Iroumé (2001) lists for each one of the 29 experimental plots precipitation, throughfall, stemflow and interception losses for given 12-month periods. The number of experimental plots and 12 month periods provide a sound data base to support the analysis.

Throughfall varied between 55 and 82% of precipitation \( P \) for “Conifers” and from 60 and 86% of \( P \) for “Broadleaves”. The group “Conifers” includes introduced conifers species such as *Pinus radiata* and Douglas-fir as well as the native *Fitzroya cupressoides* (Alerce), while the group “Broadleaves” considers native broadleaved and *Eucalyptus spp.*

Although the differences are not significant (as determined by the \( t \)-statistic at \( p < 0.05 \)), throughfall was higher in the coniferous stands than in the broadleaved forests. The figures for throughfall are within the ranges found by Howard (1972), Aussenac (1981), Huber (1990), Huber and Oyarzún (1992), Jiang (1993), Neal *et al.* (1993) and Viville *et al.* (1993).

For the range of precipitation, climatic conditions and time period, differences amongst species, density and age of the forests seem to have little effect on the relation between throughfall and \( P \). This may be a consequence of the similar climatic pattern of dominant winter rainfall at all the sites. In these circumstances canopy differences between the plantations and forests have only small effects on the subsequent distribution of incident rainfall. In summer time, when species, density and age of the forests do affect precipitation distribution the amount of rainfall is a small proportion of the total annual figure.
Stemflow ranged from 12 to 403 mm/year in the coniferous stands and from 18 to 131 mm/year in the broadleaved stands. The differences of stemflow between the two classes are statistically significant at $p < 0.01$. As in other studies, stemflow was only a small proportion of the incoming rainfall, varying from 1 to 13% of $P$ in the coniferous stands and between 1 and 8% of $P$ in the broadleaved forests. These figures are within the ranges found by Howard (1972), Aussenac (1981), Huber (1990), Huber and Oyarzún (1992), Jiang (1993), Neal et al. (1993) and Viville et al. (1993).

Stemflow for individual trees varied from 148 to 8807 l/tree in the coniferous stands and between 141 and 3203 l/tree in the broadleaved forests, depending upon the amount of annual rainfall and the density of the forests. Stemflow for individual trees was higher in areas of high annual rainfall and less dense forests than on the sites where annual precipitation was less and forest density higher. In the less dense forests total stemflow was lower than in the dense stands but any single tree can have large stemflow because each individual crown represents a large “stemflow catchment area”. In sites with low rainfall, forest management schemes leading to less dense plantations but large individual crowns will provide more water as stemflow to support the growth of each individual tree.

Stemflow was consistently higher in the coniferous stands than in the broadleaved stands. Because of the size of the leaves and the almost horizontal branches of the broadleaved trees, little intercepted water flowed towards the stem and thence to the ground. All the native broadleaved trees have thick and rough bark as well as abundant epiphytes and mosses which increased interception storage and further reduced flow down the stems. In *E. nitens* trees the leaves inserted along the branches are also obstacles to the flow of water.

Figure 3 shows the relationship between interception losses ($I$) and precipitation data on a 12-month time base for the different stands. In the broadleaved stands interception losses ranged
from 204 to 1097 mm/year for annual precipitation varying from 734 and 2973 mm, respectively. In the coniferous stands $I$ had a narrower range of variation from 199 to 579 mm/year for annual rainfall varying from 1628 to 2648 mm. The differences of interception between coniferous and broadleaved stands are statistically significant at $p = 0.01$.

Figure 3. The relationships between interception losses ($I$) and precipitation ($P$) for 12 month-periods for all the research sites. 
(from Huber and Iroumé, 2001)
Interception varied from 11 to 39% of $P$ in the coniferous stands and between 10 and 37% of $P$ in the broadleaved forests. These figures are within the ranges found by Howard (1972), Aussenac (1981), Huber (1990), Huber and Oyarzún (1992), Kelliher et al. (1992), Myers and Talsma (1992), Jiang (1993), Neal et al. (1993), Viville et al. (1993) and Tiktak (1994). The equations of best fit (values of $r$ were all statistically significant at $p < 0.01$) for “Conifers” and “Broadleaves” are:

“Conifers” $I = 222.76 + 0.081 P$ mm ($r = 0.596$)

“Broadleaves” $I = 44.61 + 0.253 P$ mm ($r = 0.731$)

Interception losses were higher in the broadleaved forests than in the coniferous stands. This does not agree with the findings of Zinke (1967) and Leonard (1967), who concluded that conifers intercept more water than broadleaved species, because the interfacial tension of water is higher on the surfaces of needles leading to an increase in the amount of interception. Differences in number of canopy layers, age of forests, and understorey abundance and density may partially explain the differences amongst the interception losses of the coniferous and broadleaved stands. Even-aged Monterey pine and Douglas-fir plantations are managed to maintain only dominant and co-dominant trees, forming a forest with just one canopy layer and an understorey of grasses and low shrubs. Furthermore, in areas of low precipitation, Monterey pine crowns cannot fully develop and are consequently less dense, thereby reducing canopy interception capacity. Broadleaved stands, being mainly in native forests, are more heterogeneous with respect to the number of species, and this produces multi-tiered canopies where water that drips from the higher levels can be re-intercepted by lower
canopies, thereby increasing the overall interception storage capacity of the stand. The common occurrence of mosses and epiphytes in native forests further increases this interception storage capacity.

The effects of multiple canopy layers in explaining higher interception losses in broadleaved tree stands should be carefully considered. Landsberg (1986) suggested that evaporation of the water intercepted and stored by the lower canopy layers was negligible and interception losses from the upper canopy accounted for most of the total interception. In that case, forests with a single canopy layer should evaporate intercepted water at similar rates to multiple layer stands. This supposition of Landsberg (1986) is applicable to multiple canopy layered forests where the uppermost canopy is very dense and prevents light and energy reaching to lower levels. In the Chilean native forests studied here, the density of the tallest crowns and the heterogeneity of tree species at different stages of succession permits entry of sufficient sunlight into the forests to provide enough energy to evaporate intercepted water from the lowermost canopies.

In accord with these findings, the replacement of native forests by plantations of exotic species should reduce interception losses. However, because the final effect of this replacement on water yield also depends on transpiration and other evaporative losses, it is not possible to conclude that substitution of native forests by exotic plantations will actually increase water availability. However, O’Loughlin (1988) suggests that differences in water use between different types of New Zealand forests are not large.

4.1.2. Interception loss and age of the stand

The effect of aging of a stand upon interception loss was analyzed in a Monterey pine stand (25-years-old at the beginning of the research period, seven years of data are available) and a
native broadleaved stand the age of which can only be estimated at between 150 to 200-years-old (eight years of data were available within a period of nine years). These stands are characterized as sites “1a” and “4a” in Huber and Iroumé (2001).

Interception losses in the Monterey pine stand increased from 11 to 22% of $P$ between the first year (1982) and the final year (the seventh year of measurement, 1988) of the data collection period, Figure 4. The increase in interception losses for this Monterey pine stand was associated with a decrease in throughfall from 76 to 70% of $P$ and a reduction in stemflow from 13 to 8% of $P$ from 1982 to 1988, respectively. Both throughfall and stemflow decreased almost linearly over this period. The decrease in throughfall can be explained by the tendency for branches of the Monterey pine trees to become increasingly horizontal with age: this increases their interception capacity. At the same time more horizontal branches reduce the flow of intercepted water towards the stem, thereby decreasing stemflow.
The native mixed broadleaved stand behaved rather differently to the Monterey pine forest plot. Interception loss decreased almost linearly from 37 to 26% of $P$ between the first and final year of study (Figure 4), associated mainly with an increase in throughfall from 62 to 73%. Stemflow remained stable, accounting for little more than 1% of $P$ during these nine years, the exception being year 4 (1989) when stemflow was 7% of $P$. The decrease of interception loss of this stand cannot be explained by the natural dynamics of the tree species.
forming this Roble-Raulí-Coihue forest type. This 150- to 200-year-old forest had reached its climax state and the aerial biomass and its interception capacity would be expected to be stable. The decrease in interception monitored in this research period was associated with a continuous reduction of interception capacity of the bamboo species *Chusquea quila* (Mol.) Kunth., forming the dense understorey. Every 20 to 25 years this native bamboo species enters into a reproductive climax when it flowers, seeds, dries, loses all leaves and then dies. This climax phase is not instantaneous and can last for a few years. In these types of forests, large scale changes in interception capacity can occur as a result of natural catastrophes (e.g. landslides, tectonism, and volcanism) or of more local changes such as tree fall or the bamboo reproductive climax phase described above.

### 4.2. Rainfall redistribution on event basis

#### 4.2.1 Throughfall, stemflow and interception on event basis

For a 26 month period, between 1 February 1998 and 31 March 2000, total precipitation, throughfall, stemflow and interception losses were measured for a managed broadleaved native forest and a Douglas-fir plantation, Iroumé and Huber (2002). The study took place within the Malalcahuello Forest Reserve, IXth Region, Chile, located between 71º28´ and 71º35´ west and 38º23´ and 38º30´ south, in the south facing foothills of the Lonquimay volcano.

Total values for precipitation, throughfall, stemflow, net precipitation and interception losses for the study period and expressed as a percentage of $P$ are shown in Table II of Iroumé and Huber (2002). In this Malalcahuello site, throughfall and stemflow in the Douglas-fir stand were lower than in the native broadleaved forest. This could be due to the presence of rauli in
the broadleaved forest (raulí is a deciduous species that makes up 14% of the total horizontal projection of crown cover) and its 86% of ground cover compared with the 97.5% of the plantation.

The values for interception ($I$, expressed as a percentage of $P$) found in this study, both for the broadleaved native stand and the Douglas-fir plantation plot, were slightly lower than the ranges reported by Aussenac (1981), O’Loughlin (1988), Neal et al. (1993) and Tiktak (1994) in forests with similar characteristics (see Table III of Iroumé and Huber, 2002). It is possible that the concentration of the annual precipitation in a few months in winter can justify the lower interception rates measured in the Malalcahuello area. The differences in interception losses between the two studied forests can be explained by their distinctive characteristics, especially tree density and crown cover.

For the study period, 541 mm in the broadleaved native forest plot and 828 mm in the Douglas-fir plantation plot, corresponding to 14 and 22% of the precipitation reaching the canopy levels, were lost through interception and evaporation. Higher interception losses in the Douglas-fir plantation plot compared with that in the native forest do not agree with the findings of Huber and Iroumé (2001). They found that in Chile, using annual values, interception in broadleaved forests was always higher than in coniferous stands. In this study, higher values of $I$ in the plantation forest might be associated with the management scheme applied in the native forest, which was thinned to leave only the best quality stems, thereby resulting in lower crown area and reduced interception loss. The data presented in this paper cover a period of 26 months and these values represent the long term conditions for throughfall, stemflow and $I$ in both types of forest covers at the studied plots.
A total of 230 individual rain storms were recorded between 1 February 1998 and 31 March 2000. Of them, only 166 generated some component of net precipitation while in the other 64 events all the incoming precipitation was intercepted by the canopies.

Comparing the rainfall pattern of these 64 storms with those from the 10 individual storms with lower throughfall or stemflow, it is possible to conclude that intensity seemed to have the greatest influence in the initiation of net precipitation. For the 64 storms, mean intensities ranged from 0.01 to 0.93 mm/h with an average of 0.13 mm/h, while the intensities for the events where net precipitation initiated varied from 0.1 to 1.5 mm/h with an average of 0.34 mm/h. For all the 166 events producing net precipitation, mean intensities where between 0.1 and 8.45 mm/h with an average of 1.17 mm/h.

Besides rainfall intensity, throughfall was only significant when storm total precipitation exceeded 1.5 mm in the native forest and 2 mm in the Douglas-fir plantation, and stemflow started for storm total precipitation exceeding ≈7 and 9 mm for native forest and Douglas-fir, respectively.

Throughfall was not statistically different between the native forest and the Douglas-fir plantation, but the differences of stemflow between the native forest and the Douglas-fir plantation were statistically significant at $p < 0.01$ The relationships between throughfall and $P$ as well as between stemflow and $P$ for each individual storm and forest type are shown in Figures 4 and 5 of Iroumé and Huber (2002).

Differences of interception losses for individual storms between the Douglas-fir plantation and the native forest were statistically significant ($p < 0.01$). Interception losses were lower in the native forest than in the Douglas-fir plantation probably due to the fact that the broadleaved stand is less dense than the plantation and its crown cover is more permeable.
because some of the species forming this forest type lose their leaves, especially during the winter months where precipitation is concentrated.

The relationships between $I$ (expressed as a percentage of $P$) and $P$, for each individual storm and forest cover, are shown in Figure 5. The equations of best fit (values of $r$ are statistically significant at $p < 0.01$) are:

Native forest  
$I \% = 56.45 \times P^{-0.281}$  
(n = 166, $r = 0.641$)

Plantation  
$I \% = 66.39 \times P^{-0.307}$  
(n = 166, $r = 0.738$)

In Figure 5 several pairs of events having relatively similar $P$ but different $I$ are marked. Rainfall characteristics of these events and the analysis of the interception processes occurred in these storms are presented in Iroumé and Huber (2002).
Figure 5. Interception (as a percentage of precipitation) versus precipitation. (from Iroumé and Huber, 2002)
At this Malalcahuello site, precipitation, throughfall, stemflow and interception losses were studied separately in each forest for both the dormant and growing periods. A supposition was made in order than differences in forest cover (especially in the native broadleaved stand because of the presence of rauli which losses its leaves in the dormant period) between winter and summer could generate different interception patterns. The results show that the differences of interception losses expressed as a percentage of precipitation between the growing and the dormant periods for both the native forest and the Douglas-fir plantation were not statistically significant at a 0.05 level, Iroumé and Huber (2002). These results show that these forests generate particular interception patterns which are not strongly associated with the variation in crown cover throughout the year, but defined more by type of rainfall and meteorological conditions. The concentration of precipitation during the vegetation dormant period, rainfall intensity, duration and frequency, temperature, wind speed, humidity and atmospheric demand for water vapor conditioned interception losses in the Malalcahuello site.

4.2.2 Effects of forest cover on intensity-duration-frequency relationships

This research investigated the effects of forest cover on intensity-duration-frequency relationships using a stochastic model to extrapolate measured rainfall and throughfall to throughfall expected during extreme events. Data was obtained from five Douglas-fir study sites, one from a Chilean forest (Malalcahuello) and the other four from Northern American Douglas-fir forests.

Comparing intensity-duration-frequency curves of throughfall simulations with rainfall simulations showed a general reduction of extreme precipitation events by the canopy (see Figure 10 in Keim et al., 2004). This reduction in intensity averaged about 15-20% for all
durations and return periods; however, the reduction varied with event frequency and duration. Intensity reduction by the canopy was constant across the full range of durations for low return period events. Rainfall intensities of large, high return period events were reduced more at short durations and less at long durations.

The difference between intensity-duration-frequency curves of rainfall and throughfall was also quantified by the difference in return periods of events of a given magnitude. This type of analysis allows the frequency of events above threshold values of interest to be estimated, such as precipitation intensity and duration thresholds to cause landsliding. Return intervals for throughfall events equivalent to 10 and 20-y precipitation events ranged between 15 to 32 years and from 29 to 52 years depending on duration, respectively. These results suggest that hillslopes under forest canopies are likely to experience destabilizing hydrological conditions with only the 31 to 61% of the frequency experienced by hillslopes in openings.

4.3. Runoff and peak flows

4.3.1 Summer runoff and stormflow for different forest covers

Summer runoffs and stormflows at La Reina catchment were studied for periods under pre-harvesting (December to March of the years 1997/98 and 1998/99) and post-harvesting (December to March of the years 1999/2000 and 2000/01) conditions. Also, runoffs and stormflows registered in the Los Pinos, Los Ulmos1 and 2 and La Reina catchments were compared for two summer periods (December 1999 to March 2000 and December 2000 to March 2001).
4.3.1.1 *Summer runoff and peak flows for pre and post-harvesting conditions*: Water discharge from the La Reina catchment for periods under pre-harvesting (December to March of the years 1997/98 and 1998/99) and post-harvesting (December to March of the years 1999/2000 and 2000/01) conditions, expressed in daily mean discharge is presented in Figure 4 in Iroumé *et al.* (2005a).

Daily summer discharges in the two post-harvesting periods (years 1999/2000 and 2000/01) are higher than those measured in the pre-harvesting condition (years 1997/98 and 1998/99). However, this increase in summer flows can not be immediately explained by the reduction of the forest cover, since total precipitation in the two post-harvesting periods is significantly higher than those registered in the two pre-harvesting periods (see Table 4 in Iroumé *et al.*, 2005a). The effect of forest removal in runoff is analysed using a double mass approach comparing data from La Reina with Los Pinos as the control. Figure 6 shows the relationship between accumulated daily runoff in La Reina and Los Pinos for the 4 summer periods.
A noticeable change in the slope of the accumulated runoff occur in 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

Figure 6. Runoff double mass curve analysis between Los Pinos and La Reina catchments for the four studied summer periods.
(from Iroumé et al., 2005a)
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 2000-2001 clearly indicates the effect of timber harvesting in this catchment.

Storms of similar magnitude registered in each of the studied periods were selected (Iroumé et al., 2005a). The two rains of the 1997/98 and 1998/99 pre-harvesting periods generated differences between the maximum instantaneous discharge and the flow at the beginning of the storm (baseflow level) of 4.5 l/s (see Figure 7 in Iroumé et al., 2005a). In the storms of the 1999/2000 and 2000/01 post-harvesting periods, this difference increased to 7.8 and 9.3 l/s, respectively. After the final forest harvest, the differences between maximum instantaneous discharge and the flow at the beginning of the storm almost duplicated those registered in similar rainfall events which occurred when the catchment was fully forested. Increases in summer peak flows after clearcutting have been monitored by Dickison et al. (1981) and Jones and Grant (1996).

4.3.1.2 Summer runoff and stormflows in four experimental catchments: Water discharge from the Los Pinos, Los Ulmos1 and 2 and La Reina catchments for two summer periods (December 1999 to March 2000 and December 2000 to March 2001), expressed as daily mean specific discharge (l/s/ha) are presented in Figures 2 and 3 in Iroumé et al. (2005a). In these two figures 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 and 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 low baseflow registered in La Reina is noticeable, especially when compared with those from the Los Ulmos catchments, and could be associated to groundwater fluxes underneath the gauging station.

The three major events registered in the 1999/2000 and 2000/2001 summer periods (see Figures 2 and 3 in Iroumé et al., 2005a) were used to analyse the behaviour of the catchments for the maximum daily specific flows. In these three events the highest daily specific discharges happen in the catchments of smaller area. In Los Pinos, owing to its larger size and higher soil water storage capacity, specific discharges were significantly smaller, reaching 0.38, 0.51 and 0.52 l/s/ha for events 1, 2 and 3, respectively.

The maximum daily specific discharges were 0.86, 1.08 and 1.09 l/s/ha for event 1 (initiated between 8 and 9 February 2000) and 0.63, 0.80 and 1.11 l/s/ha for event 2 (initiated the 29th of January 2001), in the Los Ulmos1, Los Ulmos2 and La Reina catchments, respectively. In the third event (initiated between the 7 and 9 March 2001), although the maximum specific discharge at La Reina was again higher than in the two Los Ulmos catchments, Los Ulmos1 registered a higher maximum daily discharge than Los Ulmos2.

Differences in size of the catchments, slopes steepness, road density, site preparation techniques and extent of affected area along with vegetal cover, affect hillslope hydrology and flowpaths thus discharge generation processes are not the same between different events (Harr et al., 1979; Jones and Swanson, 2001).

In Table 9 of Iroumé et al. (2005a) the values of the precipitation, total runoff, runoff coefficient, quick and base flow volumes for the two summer periods (December 1999 to
March 2000 and December 2000 to March 2001) are presented to compare the hydrological behaviour of the Los Ulmos1 and Los Ulmos2 catchments.

For the period 1999/2000, total runoff, runoff coefficient, quick and base flows are lower but not by very much in Los Ulmos1 than in Los Ulmos2. This reflects the effect of the higher water consumption of the *Eucalyptus nitens* plantation in Los Ulmos1, while most of Los Ulmos2 is covered with the residue of the *Pinus radiata* forest clearcut at the beginnings of year 1999.

The difference of 6.7 mm between total runoffs registered in 99/2000 at Los Ulmos1 and Los Ulmos2 increased to 21.1 mm for the period 2000/01, showing that the plantation of Los Ulmos1 increasingly consumes more water as it grows, although it will be important to confirm this tendency in the following years. These differences seem low as Rowe and Pearce (1994b) and Bari *et al.* (1996) report that, in the year that follows the final harvest, increases in total runoff of 10 to 20\% of the fallen rain can take place. Los Ulmos2 can be considered as having a “after the final harvest” condition while that of Los Ulmos1 is “with forest”, and for the period 2000/01 the 21.1 mm of difference among total runoff corresponds to only 4.8\% of the rainfall. This is low compared with the 10 to 20\% of fallen rain already mentioned, but the plantation in Los Ulmos1 is only a little more than three years old and the canopy closure has not taken place yet (that should happen toward 6 to 7 years old), so that it cannot be considered as a completely developed forest. In the next few years a bigger difference should be expected among the runoffs of both catchments, later to decrease as the plantation in Los Ulmos2 begins to consume water at levels similar to those of Los Ulmos1.

One storm per period was selected to compare the behaviour of the two catchments in the Los Ulmos site. These storms happened between 7 pm of February 9, 2000 and 8 am of February 11, 2000, and between 2 pm of January 29, 2001 and 12 pm of January 30, 2001, and their
characteristics in terms of precipitation, total runoff, runoff coefficient, quick and base flow volumes and maximum instantaneous specific discharges, as well as their hydrographs and hyetographs are presented in Iroumé et al. (2005a).

For both storms, total runoffs, runoff coefficients, quick and base flows are smaller but not by much in Los Ulmos1 in comparison with Los Ulmos2. These differences reflect the higher interception capacity of the vegetation of Los Ulmos1, confirming Chang and Watters (1984) and Fahey (1994) who found increases of runoff after forest harvesting. The small differences indicate the relatively low difference between the vegetal covers of both Los Ulmos catchments.

However, it is noticeable that the higher maximum instantaneous specific flows for both events occurred in Los Ulmos1, which has the more developed cover and the less steep topography of the two Los Ulmos catchments. Because smaller catchments generate higher specific discharges (Shaw, 1994) the size of Los Ulmos1 can explain this fact. Other factors that could be contributing are possible differences in the runoff generation processes, effects of road construction and logging system on hillslope hydrology (Keenan and Kimmins, 1993; Jones, 2000; Jones and Swanson, 2001) and environmental heterogeneity and extent of affected area (Wang et al., 1998) between both catchments. Los Ulmos1 has a higher road density (139 m/ha compared with 87 m/ha in Los Ulmos2) and a larger percentage of affected area (81% of the catchment was clearcut and reforested in 1997 while 68% of Los Ulmos2 area was clearcut and reforested in 2000). Site preparation techniques involved the use of fire in 1997 to eliminate wood residues in Los Ulmos1, while woody debris were mulched in Los Ulmos2. These three factors can also add to the explanation of higher maximum instantaneous specific flows in Los Ulmos1.
4.3.2 Annual runoff and stormflows for different forest covers

Runoffs and stormflows at La Reina catchment were studied during pre-harvesting (years 1997, 1998 and 1999) and post-harvesting (years 2000, 2001 and 2002) periods. Also, runoffs and stormflows registered in the Los Ulmos 1 and 2 and La Reina catchments were compared for the period between years 2000 and 2002.

4.3.2.1 Annual runoff and peak flows for pre and post-harvesting conditions: 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 post-harvesting period (years 2000, 2001 and 2002), Iroumé et al. (2005b). 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%).

On average, annual runoffs were 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 then analyzed using a double mass approach comparing data from La Reina and Los Pinos catchments, Figure 7. The significant increase in gradient (from 0.73 to 1.42) of the graph of the post-harvesting period 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., 2005a).

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).

As previously mentioned, mean annual runoff was 917 mm/year for the pre-harvesting period. After timber harvesting, runoff increased on average 1116 mm/year, 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.

The 110% increase in annual runoff after timber harvesting at La Reina lies in the upper part of the range reported in the introduction and reflects the size of the harvested area (79.4% of the catchment). Keppeler (1998) also confirmed that flow increase after clearcutting was
more relevant in wet temperate regions such as the one where La Reina is located. Finally, it is noteworthy that at the La Reina catchment the annual runoff increase is still important at the third year after timber harvesting.

Figure 7. Monthly runoff double mass curve analysis between Los Pinos and La Reina catchments for the 1997-2002 study period. (from Iroumé et al., 2005b)

Figure 8 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, 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.

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.
Primrose (2004) analyzed peak flows at this La Reina catchment 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). Comparing post and pre-harvesting conditions, she found that 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 9, 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.

From Figure 9 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.
4.3.2.2 Forest cover effects on annual runoffs and stormflows: Runoffs and stormflows registered in the Los Ulmos1 and 2 and La Reina catchments 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. (2005b). 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 from La Reina, Los Ulmos1 and Los Ulmos2 catchments were used to generate a relationship between annual runoff coefficient and the degree of development of the plantation. The relationship ($r^2$ of 0.73) 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 69% the year after timber harvesting to 35% after 22 years of plantation.
growth, Figure 10. 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 increase their water consumption capacities (i.e. interception and transpiration rates).

Figure 11 reveals the relationship between the size of rainfall events and the resultant peak flows at the Los Ulmos catchments. 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 10. Annual runoff depletion associated with plantation growth.
(from Iroumé et al., 2005b)
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 post-harvesting period 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). This disparity may be possibly explained in terms of size as La Reina is much larger then the two Los Ulmos catchments.
4.4. Mass balances at the Los Pinos experimental site

Solute concentrations and fluxes in rainfall, throughfall and stemflow in two forest types, and streamflow in the Los Pinos 90 ha catchment (39°44’S, 73°10’W) were measured.

4.4.1 Solute budget at the Los Pinos catchment

Bulk precipitation pH was 6.1 and conductivity was low. Cation concentrations in rainfall were low (0.58 mg Ca\(^{2+}/l\), 0.13 mg K\(^+\)/l, 0.11 mg Mg\(^{2+}/l\) and < 0.08 mg NH\(_4\)-N/l), except for sodium (1.10 mg/l), showing a similar response than in other Chilean coastal and near coastal sites. High sodium concentrations in precipitation are typical of coastal sites due to the influence of marine aerosols and was earlier described in other Chilean (Hedin and Campos, 1991; Oyarzún et al., 1998) and Northern Pacific coastal locations (Edmonds and Blew, 1997). Sodium flux was relatively less important at the Los Pinos catchment than at other sites closer to the Pacific Ocean (i.e. the Alerce Costero site, Oyarzún et al., 1998).

Unexpected high levels of nitrate depositions in rainfall (mean concentration 0.38 mg NO\(_3\)-N/l, total flux 6.3 kg NO\(_3\)-N/ha) were measured. Nitrate concentrations were about an order magnitude greater than at similar latitudes in Chile (Godoy et al., 1999; Oyarzún et al., 1998), suggesting that in the region moderate pollution occurs. High nitrate depositions occur during autumn (especially May, probably associated to the burning of crop and forest residues after harvesting) and winter (especially August, associated to the traditional use of wood stoves). Rainfall ammonium concentrations at the Los Pinos catchment, located in a predominantly forested region, were low and less than those at the National Park Puyehue, where precipitation chemistry was influenced by agricultural activities present in the Chilean
Central Valley (Godoy et al., 1999; 2001). Rainfall ammonium deposition was estimated between 0.3 and 0.8 kg NH₄-N/ha from April-December 1999.

Concentrations of soluble phosphorous in bulk precipitation and streamflow were below detection limits (< 0.09 mg/l) for all events.

Streamflow pH was 6.3 and conductivity was 28.3 µs. Stream water chemistry was also dominated by sodium (2.70 mg/l) followed by Ca, Mg and K (1.31, 0.70 and 0.36 mg/l).

Considering the solute budget at the Los Pinos catchment, macronutrients, such as calcium, magnesium and potassium were lost by the ecosystem, while nitrogen is retained. The solute budget indicated a net loss of 3.8 kg Na⁺/ha/yr, 5.4 kg Mg²⁺/ha/yr, 1.5 kg Ca²⁺/ha/yr and 0.9 kg K⁺/ha/yr, while 4.9 kg NO₃-N/ha/yr was retained by the ecosystem.

The element less retained by the Los Pinos ecosystem is magnesium, as it happens at the Alerce Costero site (Oyarzún et al., 1998). Mica shists, which are rich in micas and minerals and contain high levels of iron and magnesium, form the geologic substrate at the Los Pinos site (Donoso, 1981). Reduction of iron (Fe³⁺) and manganese (Mn⁴⁺) to soluble forms of these elements (Fe²⁺ and Mn²⁺), caused by high rainfalls, the saturation of soil pores and local floods, are likely in the Los Pinos catchment. Averaged concentrations for iron and manganese were 0.47 and 0.70 mg/l, respectively. Using water quality standards for Chile and Canada which limit maximum concentration for iron at 0.3 mg/l (quality standards of Canada and Chile) and for magnesium between 0.10 and 0.05 mg/l (Chilean and Canadian water quality standards, respectively), water discharge at the Los Pinos catchment is considered not suitable for domestic use. High levels of iron and manganese in streamflow are characteristic for the area of Valdivia.
4.4.2 Solute fluxes from two different forest covers at the Los Pinos catchment

Throughfall and stemflow chemistry at a *Radiata pine* stand and a native forest site (Siempreverde type), both located within the catchment, were compared.

Throughfall in both stands have similar pH values and were greater than precipitation pH (see Table 7 in Uyttendaele and Iroumé, 2002). Stemflow pH is generally strongly influenced by organic acids of stem tissues (Edmonds *et al.*, 1991; Parker, 1983) and therefore is more acidic than throughfall and precipitation.

Cation concentrations of stemflow and throughfall were greater than rainfall, due to interception loss of water on both forest covers, and the enrichment of nutrients caused by wash out of dry deposition, and leaching of plant tissues. The latter is also reflected by higher conductivity values in both forest stands.

An enrichment of cation deposition and retention of nitrate fluxes in both forest stands are evident. Throughfall of the native forest had higher concentrations of all cations than *Radiata pine* (the exception is nitrate fluxes with 1.3 kg NO_3-N/ha/yr in throughfall and stemflow). Yet in spite of this the conductivity was lower. By contrast, stemflow of the native forest had lower concentrations for Na and K, higher concentrations of Ca and identical concentrations of Mg; resulting in almost identical conductivity values. According to Parker (1983), generally up to 90% of potassium can result from plant nutrient leaching. Nutrient additions under native forest are mainly attributed by throughfall. Cation fluxes of throughfall in native forest are greater than in *Radiata pine*, while stemflow fluxes are lower.

Cation fluxes in net rainfall (throughfall plus stemflow) at the pine stand were generally higher (34.8 kg Na⁺/ha/yr, 21.5 kg K⁺/ha/yr, 5.1 kg Mg²⁺/ha/yr) compared to the native forest site (24.7 kg Na⁺/ha/yr, 18.9 kg K⁺/ha/yr and 4.4 kg Mg²⁺/ha/yr), however, calcium deposition beneath the native forest was higher compared to the pine stand (15.9 and 12.6 kg.
Ca\textsuperscript{2+}/ha/yr, respectively). Rapp (1969) and Wyers and Duyzer (1997) suggest higher dry deposition rates on coniferous forests compared to long leaved trees, and Rapp (1969) conclude that coniferous forests reflect better the proximity of local sources of dry deposition. Higher dry deposition rates on *Pinus radiata* caused higher sodium fluxes in net rainfall (throughfall plus stemflow) compared to the Siempreverde site.

### 4.5. Erosion and sediment transport

#### 4.5.1 Erosion rates

Erosion rates were quantified at the Los Pinos site from superficial runoff plots in years 1988, 1998 and 1999 (Iroumé *et al*., 1989; Stolzenbach, 1998; Rivas, 2000). Superficial erosion was measured during 140 days in 1988, 153 days in 1998 and 168 in 1999. Annual precipitation and rainfall during these periods were 2550 and 715 mm in 1988, 1364 and 1085 mm in 1998 and 1844 and 1532 mm in 1999. In the 1988 period rainfall was 28% of annual precipitation, and in the other two cases the rainfall was an important percentage of total annual precipitation (80% in 1998 and 83% in 1999).

In 1988, runoff plots were installed under bare soil conditions in areas with slopes of 30, 50 and 60%, and in terrains with 30% slope in a grassland site and two *Radiata pine* plantations 6 and 33 years old. Soil losses for bare soil condition were 1563, 1878 and 3926 kg/ha for slopes of 30, 50 and 60%, respectively. In the areas of 30% slopes covered with vegetation, soil losses were 133 kg/ha for the grassland site, and 75 and 70 kg/ha for the 6 and 33 years old *Radiata pine* plantations, respectively.

In 1998, 25% slope runoff plots were installed on bare soil and under 7 and 22 years old *Radiata pine* plantations, and yielded soil losses of 317, 43 and 13 kg/ha, respectively.
In 1999, 22 and 25% slope runoff plots were put under a 3 years old *Eucalyptus nitens*, a 2 years old *Radiata pine* plantations and a 23 years old *Radiata pine* plantations, and yielded soil losses of 100, 26 and 12 kg/ha, respectively.

Erosion rates from *Radiata pine* planted areas were similar in these studies (between 12 and 75 kg/ha), and much lower than erosion generated in bare soil conditions. Erosion from *Eucalyptus nitens* planted areas was much higher than the one measured the same year under *Radiata pine* plantations, which confirm Calder (1992) who found that *Eucalyptus spp* concentrate raindrops thus increasing erosivity as compared with other tree species.

A new erosion study was carried out on bare soil conditions throughout an episode of heavy rainfall occurred between mid August to mid September 2003 (311.4 mm in 25 days with three hours erosive rainfall intensity greater than 12.7 mm/h) in an area with 22% slope. The site was clearcut in January 2003 and the forest residues were piled up in rows some 80 meters apart following the contour lines. Using the $^7$Be technique, a net erosion rate of about 4300 kg/ha (4.3 t/ha with a sediment delivery ratio of 66% was estimated. The validity of the results provided by the $^7$Be conversion model was assessed through direct measurement of the depth of the soil layer lost or gained during the same rainfall period using a regular distributed pin grid, which produced a very similar erosion rate.

The 4300 kg/ha of soil lost during the episode of heavy rainfall occurred in 2003 are higher than the erosion rates between 317 and 3926 kg/ha registered in 1988 and 1998. Although these experiments took place under bare soil conditions, the differences in erosion rates could be associated to soil preparation techniques. In the 1988 and 1998 experiments, after the final forest harvest all woody residues were removed by hand to generate the “bare soil” condition in the erosion plots. On the other hand, in the 2003 study the site had been prepared for the
new plantation with heavy machinery which dragged woody residues to pile them up, which generated further soil removal and alteration and increased erosion potential.

Pilling up woody debris could be appropriate to retain eroded particles on the slope and prevent them to enter the drainage system, but erosion between the rows could be an important source of soil degradation.

4.5.2 Sediment yields in experimental catchments

Sediment-transport rating curves were derived relating the suspended sediment concentration to water discharge at the La Reina catchment. Using these rating relations to the continuous record of discharge, suspended sediment yields for years 2000 and 2002 were quantified.

Suspended sediment yield for year 2000 (the year following final harvest at the La Reina catchment) was 23.5 t/ha. For year 2002, suspended sediment yield was estimated at 11.9 t/ha, indicating an important reduction of sediment transport as vegetation develops. This reduction in sediment transport is even more important, considering that mean annual discharge for years 2000 and 2002 were 19.3 and 26.2 l/s, respectively. During both years, bedload transport was only a minor part of total sediment yield (less than 1%) which indicates that sheet erosion is the main contributor to stream sediment concentrations. In this Coastal mountain range catchment, plantation forestry-related activities will determine sediment yield ratios, rather than erosional processes in the drainage system.

Different sediment processes occur at the Rio Tres Arroyos catchment. Between 1997 and 2002, mean suspended, bedload and total sediment yields were quantified at 3165, 7257 and 10692 tons (5.3, 12.2 and 10 t/ha/year). Bedload transport is higher in this Andean catchment compared with those registered in coastal watersheds, and shows that erosion processes within the drainage network are as important as those from the catchment’s slopes.
5. CONCLUSIONS

The data presented in this paper provide an insight to the hydrological processes associated to the development of plantation forestry in Chile. Different studies have been carried out in diverse research sites and forest types and add significantly to the knowledge of the hydrological behavior of forests in the country.

In areas with annual rainfall over 1200 mm, interception losses are consistently higher for broadleaved than for coniferous stands. Because evaporation of the intercepted precipitation can represent a net addition to catchment evaporative losses, the afforestation of land previously in pasture or under cultivation should significantly reduce water yield. The replacement of native forests by plantations of exotic species should reduce interception losses, but because the final effect upon water yield also depends on transpiration and other evaporation losses, it is not possible to conclude that the substitution of native forests by plantations will increase water availability. Interception losses in a Monterey pine forest increased with age of the stand because of the tendency for the branches to become more horizontal, thereby increasing interception capacity but decreasing stemflow. In a 150- to 200-year-old native forest that had reached its climax state, a decrease in interception loss occurred during nine years of data collection related to the continuous reduction of interception by the dense understory of a bamboo species that had entered the final, reproductive phase of its life cycle. Analysis of the variability of annual throughfall, stemflow, and interception losses suggest that in sites with more restricted rainfall conditions, management measures that produce less dense forests also reduce total stemflow but increase individual tree stemflow, providing more water to support the growth of individual trees. Because in the early years of a rotation of an exotic plantation, interception loss will be much
smaller than for mature forests, and this will also probably be true for transpiration and other evaporation losses, a catchment should be managed with a range of age class plantations to maximize the availability of water.

The adopted methodology and instrumentation allowed quantification of total precipitation, throughfall, stemflow and interception losses for individual storms under two different forests in the Malalcahuello area, in the IXth Region in southern Chile, and the results add the knowledge of the rainfall redistribution and interception processes in temperate climates that characterises this site. The results showed the importance of the vegetation cover in the distribution of rainfall and interception losses. Between 1 February 1998 and 31 March 2000, some 22% and 14% of the incoming precipitation for a broadleaved native forest and a Douglas fir plantation, respectively, were transferred to the atmosphere through evaporation before reaching the forest floor. Differences between interception capacities in the Malalcahuello area seemed to be regulated more by the concentrated pattern of precipitation during the dormant period of the vegetation and other meteorological conditions and then by the density level and characteristics of the crown cover.

Intensity-duration-frequency relationships (IDF) of throughfall were developed using a stochastic model to extrapolate measured rainfall and throughfall to throughfall expected during extreme events. As far as the authors know, these are the first published IDF curves for throughfall. Comparing intensity-duration-frequency curves of throughfall simulations with rainfall simulations showed a general reduction of extreme precipitation events by the canopy. Return intervals for throughfall events equivalent to 10 and 20-y precipitation events ranged between 15 to 32 years and from 29 to 52 years depending on duration, respectively. These results suggest that hillslopes under forest canopies are likely to experience
destabilizing hydrological conditions with only the 31 to 61% of the frequency experienced by hillslopes in openings.

The reduction of vegetation cover generates increases in summer runoff and peak discharges, and the biggest effects happen after harvesting significant proportions of a forest within the catchments. The combined effect of the vegetal cover and topography explain the differences in summer runoff and maximum daily specific discharges among four experimental catchments and in the behaviour of the same catchments for individual storms. In one of these catchments, differences between the maximum instantaneous discharge and the flow at the beginning of the storm under post-harvesting conditions almost duplicated those registered in similar rainfall events occurred when the catchment was fully forested. In the two neighbouring catchments at the Los Ulmos site, the lower vegetation cover of Los Ulmos2 explains the higher summer direct runoffs and base flows. However, this catchment generated lower maximum instantaneous peak flows, probably associated with larger catchment size, lower road density and smaller percentage of affected area than Los Ulmos1. Although lower cover is associated with higher summer flows, 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.

During the three years following clearcutting of the Pinus radiata plantation that covered the 79.4% of the La Reina catchment, 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. 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 69% the year after timber harvesting to 35% 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 timber harvesting should be carefully considered to fully understand the hydrological effects of forest cover changes.

Precipitation chemistry at the Los Pinos site was similar to other near coastal unpolluted regions, except for acidity and nitrate fluxes. Differences in precipitation pH are attributed to the presence of aerosols and cation rich dusts, together with the sampling period. Nitrogen depositions are moderate compared to other studies in southern Chile. The solute budget showed a net loss of all basic cations, and because vegetation cover is moderately young, it is suggested that dry and cloud deposition are important nutrient sources for plant growth. Streamflow is not suitable for domestic due to high concentrations of iron and manganese. Troughfall and precipitation pH are similar, and less acidic than stemflow pH in the \textit{Pinus radiata} and native forest stand. Fluxes of cations in the pine stand are higher compared to the native forest, except for calcium. Higher sodium fluxes in the coniferous stand are attributed to higher dry deposition rates while higher calcium fluxes in the native forest site can be explained by higher calcium contents in vegetation.

Erosion studies successfully demonstrate the potential for using $^{7}$Be to estimate short term erosion affecting recent harvested forest areas. Results of annual sediment yield from La Reina catchment the year after clearcutting and two years since the establishment of a new plantation show important decreases of sediment transport as vegetation develops. Sediment
transport patterns in Coastal catchments show that main sediment sources correspond to sheet erosion, while in the steeper catchments located in the Andes mountains erosion processes in the drainage network become relevant.

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. Future developments of these researches should include, among others, the analysis of runoff generation processes to better understand the relation between land use changes and runoff and peakflows, considerations about the geographical links between sediment sources and drainage network to recognize the relationships between erosion and sediment yields, and the use of natural tracers to investigate water, sediment and nutrient fluxes.
6. REFERENCES


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7. SUMMARY

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. 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. 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. This suggests that future demand will have to be supplied from a diminishing, or more restricted, forest resource base. To solve this dilemma the only solution is to increasingly shift the wood harvest from natural forests to deliberately created planted forests.

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 (i.e. wilderness protection, biodiversity conservation, and recreation and carbon sequestration demands). Although a key factor of plantation expansion is going to be economics, as planted forests are probably the most capital-intense industry in existence, the hydrological effects of large scale afforestation and deforestation and water allocation issues could constrain additional development of planted forests. The study of forest-water related issues will be required in order to provide recommendations regarding forest management options, which could allow adequate tree growth rates but are compatible with restrictions on water availability, both in quantity and quality.

In Chile, the forest sector participates with the 3.6% of the national GDP and the 12.5% of total exports. Near the 95% 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 300,000 ha at the beginning of the 1970s to 2,100,000 hectares in 2002 and are established with exotic fast growing species where Pinus radiata and Eucalyptus spp. represent the 75 and 17%, respectively. The importance of the economic role of the forest sector is likely to increase. Forestry has a real opportunity for expansion 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, and the existing 4.5 million hectares of potentially productive
native forests. 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.

The hydrological consequences of intensive forest operations on water yield and quality have received much attention. At a global scale afforestation and deforestation are the most important land use changes in terms of hydrological effects. Although the establishment of plantations on land previously in pasture or under cultivation has protected many areas from further erosion, large scale forest operations can severely affect water, nutrient, and sediment cycling within a catchment. 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 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. As part, if not the whole, of such interception losses represent an addition to net catchment evaporative losses, this process may dominate water availability.

Regarding runoff, several studies show that after timber harvesting -and even after intense thinning- annual streamflow increases significantly from pre-harvesting conditions. The effects of forests on summer flows is even greater because interception and transpiration capacity are at the highest levels during summer months, since forests are in full vegetative period and fully leaved. Higher transpiration losses because of the deeper root systems of trees reduce soil water reserves which sustain base flows during summer. Peak flows also increase after timber harvesting, but the effect of storm type is still controversial as some studies report effects on 100-year return period storms whereas in others any change were detected 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, is more
pronounced after clearcuttings than partial harvestings and more significant in wet temperate regions. Major effects occur up to three years after logging, afterwards, because of vegetation regrowth, streamflow quickly returns to baseline levels.

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. 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 (absorption and desorption). 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, plant tissue composition, bark roughness, the accompanying vegetation and associative wildlife.

Many studies show that one of the most important water quality problem associate with forestry is sedimentation. 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. Sources of sediment include roads, bare soil on steep slopes, cutbanks, slope failures and debris flows, and streambank erosion and channel scour. 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 can greatly reduce the magnitude of erosion and sedimentation effects.

The main objective of this research is to provide sound information to better understand the hydrological processes associated to the development of plantation forestry in Chile. The studies have been carried out in different forest types and they are intended to add to the knowledge of the hydrological effects of plantation forestry in Chile and provide recommendations regarding forest management options, which allow adequate tree growth rates but are compatible with restrictions on water availability.

The specific objectives are: quantify and compare canopy interception losses for different forest types and locations on 12-month based periods; quantify and compare canopy interception losses for one research site and two different forest types on rainfall event basis; estimate the effects of forest cover on intensity-duration-frequency relationships of rainfall
and extreme events with a stochastic model; analyze runoff and peak flow during low-flow periods, comparing water production in pre- and post-harvesting periods and from catchments with different forest covers; compare annual water production and peak flows in pre- and post-harvesting conditions and from catchments with different forest covers; determine the solute budget and stream water quality, compare bulk precipitation chemistry with other sites in Chile and evaluate net rainfall fluxes (throughfall and stemflow) between a plantation and a native forest stand; and, analyze erosion and sediment transport rates in forest catchments.

Rainfall redistribution and canopy interception on 12-month basis has been studied on nine research sites with 29 experimental plots. In one of these sites, a deeper analysis comparing rainfall redistribution processes on event basis in a broadleaved native forest and in a coniferous plantation was carried out. Rainfall and throughfall data from the Douglas-fir stand at this last site, plus additional original information for the same site, was assembled with data from four Northern American Douglas-fir forests, to investigate with a stochastic model the effects of forest cover on intensity-duration-frequency relationships.

Water production and sediment transport have been studied in five experimental catchments, with areas ranging from 593 and 10.8 ha. Comparisons of runoff and peak flows in pre- and post-harvesting periods and for different forest covers have been carried out, both in dry summer periods and on annual basis.

Nutrient fluxes were studied in one of these experimental catchments, with additional facilities to determine rainfall, streamflow, stemflow and throughfall chemistry.

Erosion processes have been studied in two areas, quantifying erosion rates from experimental plots and using the $^7$Be technique.

Finally, suspended sediment concentration and annual sediment yield have been studied in several of the experimental catchments.

Precipitation, throughfall, stemflow and interception losses for given 12-month periods and different forest covers were measured in 29 experimental plots. Data is summarized for two forest cover groups, one being the group “Conifers” which includes introduced conifers species such as Pinus radiata and Douglas-fir as well as the native Fitzroya cupressoides (Alerce), and the other the group “Broadleaves” that considers native broadleaved and Eucalyptus spp. Throughfall was higher in the coniferous stands than in the broadleaved forests, and varied between 55 and 82% of precipitation ($P$) for “Conifers” and from 60 and
86% of $P$ for “Broadleaves” (differences are not significant). For the range of precipitation, climatic conditions and time period, differences amongst species, density and age of the forests seem to have little effect on the relation between throughfall and $P$. This may be a consequence of the similar climatic pattern of dominant winter rainfall at all the sites. In these circumstances canopy differences between the plantations and forests have only small effects on the subsequent distribution of incident rainfall. In summer time, when species, density and age of the forests do affect precipitation distribution the amount of rainfall is a small proportion of the total annual figure. Stemflow ranged from 12 to 403 mm/year in the coniferous stands and from 18 to 131 mm/year in the broadleaved stands (differences are statistically significant). Stemflow was only a small proportion of the incoming rainfall, varying from 1 to 13% of $P$ in the coniferous stands and between 1 and 8% of $P$ in the broadleaved forests. Stemflow for individual trees varied from 148 to 8807 l/tree in the coniferous stands and between 141 and 3203 l/tree in the broadleaved forests. Stemflow for individual trees was higher in areas of high annual rainfall and less dense forests than on the sites where annual precipitation was less and forest density higher. In the broadleaved stands interception losses ($I$) ranged from 204 to 1097 mm/year for annual precipitation varying from 734 and 2973 mm, respectively. In the coniferous stands $I$ had a narrower range of variation from 199 to 579 mm/year for annual rainfall varying from 1628 to 2648 mm (differences of interception between coniferous and broadleaved stands are statistically significant). Interceptation varied from 11 to 39% of $P$ in the coniferous stands and between 10 and 37% of $P$ in the broadleaved forests. Interception losses were higher in the broadleaved forests than in the coniferous stands, and in accord with these findings the replacement of native forests by plantations of exotic species should reduce interception losses. However, because the final effect of this replacement on water yield also depends on transpiration and other evaporative losses, it is not possible to conclude that substitution of native forests by exotic plantations will actually increase water availability. Though, studies developed in New Zealand suggest that differences in water use between different types of forests are not large. For a 26 month period, total precipitation, throughfall, stemflow and interception losses were measured at event basis for a managed broadleaved native forest and a Douglas-fir plantation. The study took place within the Malalcahuello Forest Reserve, IXth Region, Chile, located between 71º28´ and 71º35´ west and 38º23´ and 38º30´ south, in the south facing foothills of the Lonquimay volcano. A total of 230 individual rain storms were recorded during the study,
but only 166 generated some component of net precipitation while in the other 64 events all the incoming precipitation was intercepted by the canopies. Comparing the rainfall pattern of these 64 storms with those from the 10 individual storms with lower throughfall or stemflow, it is possible to conclude that intensity seemed to have the greatest influence in the initiation of net precipitation. For the 64 storms, mean intensities ranged from 0.01 to 0.93 mm/h with an average of 0.13 mm/h, while the intensities for the events where net precipitation initiated varied from 0.1 to 1.5 mm/h with an average of 0.34 mm/h. For all the 166 events producing net precipitation, mean intensities where between 0.1 and 8.45 mm/h with an average of 1.17 mm/h. Besides rainfall intensity, throughfall was only significant when storm total precipitation exceeded 1.5 mm in the native forest and 2 mm in the Douglas-fir plantation, and stemflow started for storm total precipitation exceeding ≈7 and 9 mm for native forest and Douglas-fir, respectively. For individual storms, throughfall was not statistically different between the native forest and the Douglas-fir plantation, but the differences of stemflow and interception losses between the native forest and the Douglas-fir plantation were statistically significant. Statistically significant relationships between \( I \) (expressed as a percentage of \( P \)) and \( P \) were developed for both the Native forest (\( n = 166, r = 0.641 \)) and the Plantation (\( n = 166, r = 0.738 \)). At this Malalcahuello site, precipitation, throughfall, stemflow and interception losses were studied separately in each forest for both the dormant and growing periods under the supposition that differences in forest cover (especially in the native broadleaved stand because of the presence of deciduous species which losses its leaves in the dormant period) between winter and summer could generate different interception patterns. The results show that the differences of interception losses expressed as a percentage of precipitation between the growing and the dormant periods for both the native forest and the Douglas-fir plantation were not statistically significant, and that these forests generate particular interception patterns which are not strongly associated with the variation in crown cover throughout the year, but defined more by type of rainfall and meteorological conditions. The concentration of precipitation during the vegetation dormant period, rainfall intensity, duration and frequency, and temperature, wind speed, humidity and atmospheric demand for water vapor conditioned interception losses in the Malalcahuello site.

Rainfall and throughfall data from the Douglas-fir stand at the Malalcahuello site was assembled with data from four Northern American Douglas-fir forests, to investigate the effects of forest cover on intensity-duration-frequency relationships using a stochastic model.
to extrapolate measured rainfall and throughfall to throughfall expected during extreme events. Comparing intensity-duration-frequency curves of throughfall simulations with rainfall simulations showed a general reduction of extreme precipitation events by the canopy. This reduction in intensity averaged about 15-20% for all durations and return periods; however, the reduction varied with event frequency and duration. Return intervals for throughfall events equivalent to 10 and 20-y precipitation events ranged between 15 to 32 years and from 29 to 52 years depending on duration, respectively (i.e. these results suggest that hillslopes under forest canopies are likely to experience destabilizing hydrological conditions with only the 31 to 61% of the frequency experienced by hillslopes in openings). As far as the authors know, these are the first published IDF curves for throughfall.

Summer runoffs and stormflows at La Reina catchment were studied for periods under pre-harvesting (December to March of the years 1997/98 and 1998/99) and post-harvesting (December to March of the years 1999/2000 and 2000/01) conditions. Also, runoffs and stormflows registered in the Los Pinos, Los Ulmos1 and 2 and La Reina catchments were compared for two summer periods (December 1999 to March 2000 and December 2000 to March 2001). The effect of forest removal in summer runoff at La Reina was analysed using a double mass approach comparing data from La Reina with Los Pinos as the control. A noticeable change in the slope of the accumulated runoff occur in 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 2000-2001 clearly indicates the effect of timber harvesting in this catchment. Storms of similar magnitude registered in each pre and post-harvesting studied periods were analyzed, and the two rains of the 1997/98 and 1998/99 pre-harvesting periods generated differences between the maximum instantaneous discharge and the flow at the beginning of
the storm (baseflow level) of 4.5 l/s, while in the storms of the 1999/2000 and 2000/01 post-
harvesting periods, this difference increased to 7.8 and 9.3 l/s, respectively.
Runoffs and stormflows at La Reina catchment were studied during pre-harvesting (years
and stormflows registered in the Los Ulmos 1 and 2 and La Reina catchments were compared
for the period between years 2000 and 2002. At La Reina, 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 post-harvesting period (years 2000, 2001 and 2002). 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\%).
On average, annual runoffs were 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 \textit{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 effect of forest removal on runoff was then analyzed using a double
mass approach comparing data from La Reina and Los Pinos catchments. The significant
increase in gradient (from 0.73 to 1.42) of the graph of the post-harvesting period 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. Projecting the 1997-1999 cumulated runoff trend beyond January 2000, it is
possible to estimate “virtual” annual runoff for years 2000, 2001 and 2002. Comparing these
estimations with the measured annual runoffs for the same years, the double mass analysis
indicates a mean increase of 1013 mm/year. As previously mentioned, mean annual runoff
was 917 mm/year for the pre-harvesting period. After timber harvesting, runoff increased on
average 1116 mm/year, 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
cause 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 \textit{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. 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.

Relationships between the size of rainfall events and the resultant peak flows at La Reina were developed independently for the pre- and post-harvesting periods. 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. 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) 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, therefore supporting the hypothesis that the increases in peak flows are associated to the differences in land cover between the two periods.

Runoffs and stormflows registered in the Los Ulmos1 and 2 and La Reina catchments 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). 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. The difference in interception losses between these two catchments (220-320 mm/year) may explain the difference in runoff.

Data from La Reina, Los Ulmos1 and Los Ulmos2 catchments were used to generate a relationship between annual runoff coefficient and the degree of development of the
plantation. The relationship ($r^2$ of 0.73) 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 69% the year after timber harvesting to 35% after 22 years of plantation growth. 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 increase their water consumption capacities (i.e. interception and transpiration rates).

Precipitation chemistry at the Los Pinos site was similar to other near coastal unpolluted regions, except for acidity and nitrate fluxes. Differences in precipitation pH are attributed to the presence of aerosols and cation rich dusts, together with the sampling period. Nitrogen depositions are moderate compared to other studies in southern Chile. The solute budget showed a net loss of all basic cations, and because vegetation cover is moderately young, it is suggested that dry and cloud deposition are important nutrient sources for plant growth. Streamflow is not suitable for domestic due to high concentrations of iron and manganese. Throughfall and precipitation pH are similar, and less acidic than stemflow pH in the Pinus radiata and native forest stand. Fluxes of cations in the pine stand are higher compared to the native forest, except for calcium. Higher sodium fluxes in the coniferous stand are attributed to higher dry deposition rates while higher calcium fluxes in the native forest site can be explained by higher calcium contents in vegetation.

Erosion studies successfully demonstrate the potential for using $^7$Be to estimate short term erosion affecting recent harvested forest areas. Results of annual sediment yield from La Reina catchment the year after clearcutting and from two years after the establishment of a new plantation show important decreases of sediment transport as vegetation develops. Suspended sediment yield for year 2000 (the year following final harvest at the La Reina catchment) was 23.5 t/ha, while in 2002 suspended sediment yield was estimated at 11.9 t/ha, indicating an important reduction of sediment transport as vegetation develops. This reduction in sediment transport is even more important, considering that mean annual discharge for years 2000 and 2002 were 19.3 and 26.2 l/s, respectively. Sediment transport patterns in Coastal catchments show that main sediment sources correspond to sheet erosion, while in the steeper catchments located in the Andes mountains erosion processes in the drainage network become relevant.

The data presented in this document provide an insight to the hydrological processes associated to the development of plantation forestry in Chile. Different studies have been
carried out in diverse research sites and forest types and add significantly to the knowledge of the hydrological behavior of forests in the country. Because evaporation of the intercepted precipitation can represent a net addition to catchment evaporative losses, the afforestation of land previously in pasture or under cultivation should significantly reduce water yield. The replacement of native forests by plantations of exotic species should reduce interception losses, but because the final effect upon water yield also depends on transpiration and other evaporation losses, it is not possible to conclude that the substitution of native forests by plantations will increase water availability. In sites with more restricted rainfall conditions, management measures that produce less dense forests also reduce total stemflow but increase individual tree stemflow, providing more water to support the growth of individual trees. Because in the early years of a rotation of an exotic plantation, interception loss will be much smaller than for mature forests, and this will also probably be true for transpiration and other evaporation losses, a catchment should be managed with a range of age class plantations to maximize the availability of water. In this wet temperate regions, timber harvesting had a greater effect in increasing annual runoff compared to peak flows. 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. Future developments should include, among others, the analysis of runoff generation processes to better understand the relation between land use changes and runoff and peakflows, considerations about the geographical links between sediment sources and drainage network to recognize the relationships between erosion and sediment yields, and the use of natural tracers to investigate water, sediment and nutrient fluxes.