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# Hydrological Characteristics at Hilly Catchment in a Semi-Arid Region, Chile

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## Abstract

The Alto Loica experimental site was established to achieve some understanding of the hydrological characteristics and the effects of afforestation on soil and water conservation in semi-arid regions in Chile. Hydrological measurements were taken in the 16.25-ha catchment for seven years. Because of the high variability of annual rainfall, there was a drought year in which streamflow disappeared throughout the year. As the catchment contains intermittent streams, mean annual baseflow is only 5.9% of mean annual rainfall, while mean annual evapotranspiration is 62.6% of that. The seasonal fluctuations of soil moisture storage suggest that moisture conditions during the period of December through March may be the driest ones for the growth of vegetation. While Horton overland flow occurs over grassy and shrub covered hillside during high rainfall intensities, it contributes largely to sharp hydrograph peaks. During large rainstorms, the mean runoff coefficient was more than 50%. Hence, measures to reduce overland flow are required for afforestation as well as soil and water conservation.

**Discipline:** Forestry and forest products
**Additional key words:** Forest hydrology, water budget, overland flow, afforestation

## Introduction

Desertification of less arid regions may be a result of overgrazing and exploitation of vegetation beyond the land's productive potential[12]. A typical case of desertification in Latin America is found in semi-arid regions in the Republic of Chile. About 500,000 ha of degraded natural vegetation and soil productivity exist from the Fourth Region to the Metropolitan Region. Before European colonization, the areas were mainly covered with steppe forest. Excessive felling for firewood, deforestation by an expansion of agriculture and overgrazing during the past century denuded the land and created gullied areas. Since the areas belong to the 200 to 400 mm annual rainfall zone, it is difficult for the destroyed vegetation to recover without restoration treatments such as contour trenches and bio-engineering[3].

Because of these circumstances, the erosion control and afforestation project was initiated in 1993 by Corporacion Nacional Forestal (CONAF) in collaboration with Japan International Cooperation Agency (JICA). The project established a small experimental catchment to assess the effects of restoration treatments and afforestation on soil and water conservation in semi-arid regions. Hydrological measurements at the catchment commenced in August 1994 by the project. During the seven years of monitoring, a drought year and a wet year caused by the La Niña and the El Niño phenomenon were observed. These records lead to a better understanding of an outline of hydrological characteristics in the area. Characteristics of runoff, infiltration and subsurface flow of water in arid and semi-arid regions have been described by Issar and Resnick[10], but there is no such description in Latin America. In addition, there are fewer catchment experiments in semi-arid regions than in humid regions, although it is required for assessing the effect of vegetation changes[1,14].

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This paper describes an original set of hydrological data obtained from a small catchment with the objective to understand the hydrological characteristics in a semi-arid region in Chile.

## Methods

### 1. Site description

The Alto Loica project site (34º00′ S, 71º30′ W) is located about 120 km southwest of Santiago, the capital of Chile (Fig. 1). The area consists of gentle hills of 200 to 350 m elevation in the Cordillera de la Costa, a 1,000 km long hilly region along the Pacific seaboard.

The gradient of hillslope varies from 5 to 15 degrees. The area has been used for wheat cropping and / or grazing after deforestation. Thin *Acacia caven* about 2 m in height and grass (mainly *Avena barbata* and *Bromus mollis*), the so-called Estepa de Espino, can be seen over the area. The original dominant species were *Acacia caven*, *Maytenus boaria*, *Quillaja saponaria, Baecharis linearia,* and *Prosopis chilensis*[3]. An experimental 16.25 ha catchment (280–330 m elevation) was established at the foot of a hill located in the central part of the project site.

Köppen's system classifies the climate as Csb: it is a Mediterranean climate with precipitation in winter. The mean annual rainfall ($\mu$) for the period 1961 to 1991 at Longovilo station (33º54′ S, 71º24′ W; 150 m elevation), the nearest meteorological station which might be included by an isohyetal map, was 398.5 mm with a standard deviation ($\alpha$) of 193.8 mm. Approximately 88% of annual rainfall occurred from May to September. The mean annual temperature was 15.3ºC and the average maximum and minimum monthly temperatures were 32.2ºC in January and 3.4ºC in July, respectively.

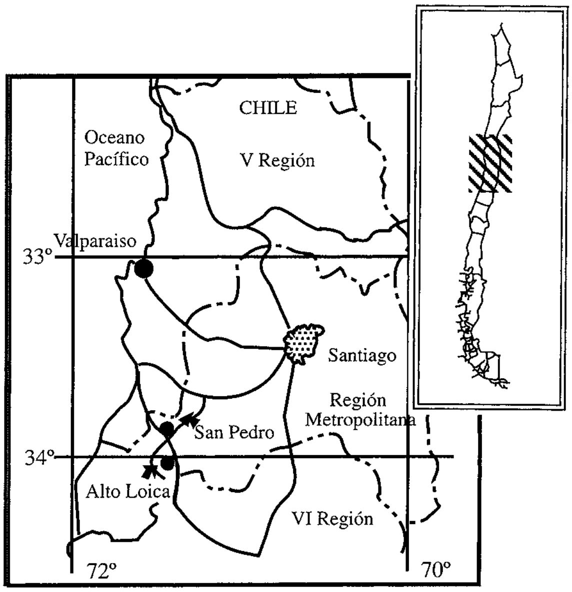


**Fig. 1. Location of experimental site**

Surface soils of the catchment, which is classified as an Ap-horizon with little organic matter, have a sandy clay texture. Soil depth of the thin A-horizon varies from 10 to 40 cm by micro-topography. The saturated hydraulic conductivity of the A- and B-horizon is $10^{-3}$ cm/s and $10^{-3}$ to $10^{-4}$ cm/s, respectively. The soil hardness of the soil surface is 20 to 30 kg/cm$^2$ in early dry season and about 100 kg/cm$^2$ in the drier season. The area is underlain by weathered granite. Outcrops of bedrock could not be seen except in the gullied areas.

### 2. Hydrological data

Rainfall within the catchment was measured with a tipping-bucket rain-gauge installed at the gauging station and two storage rain-gauges at the middle of the hillside. Hourly, daily and monthly summaries of rainfall were completed.

Streamflow from the catchment was measured with a 60-degree, sharp crested weir with a stilling pond equipped with a continuous stage recorder. The rating curve for the weir was determined by volume measurements at different stages. The daily total discharge passing the gauging station was expressed as a water depth over the catchment. Every instantaneous peak was read from charts and the peak flow rate (L/s) was calculated. Daily, monthly and annual summaries of streamflow expressed as water depth equivalents were completed from August 1994 to December 2001. The water year of the catchment is the same as a calendar year.

Stormflow is separated from storm hydrographs (baseflow separation) by drawing a straight line from the rising point to the characteristic point of the falling segment on semilogarithmic paper based on Chow[2]. Stormflow duration is defined as the interval from the time of rise to the end of stormflow. Annual stormflow is obtained by totaling the stormflow estimated by baseflow separation. Annual baseflow is obtained by subtracting the annual stormflow from annual streamflow. Therefore, the annual water budget consists of annual rainfall, stormflow, baseflow and a loss component.

## Results and discussion

### 1. Characteristics of annual rainfall

The rainfall recorded by the tipping-bucket rain-gauge was approximately the same as that of storage rain-gauges for separated storm events. Therefore, the areal

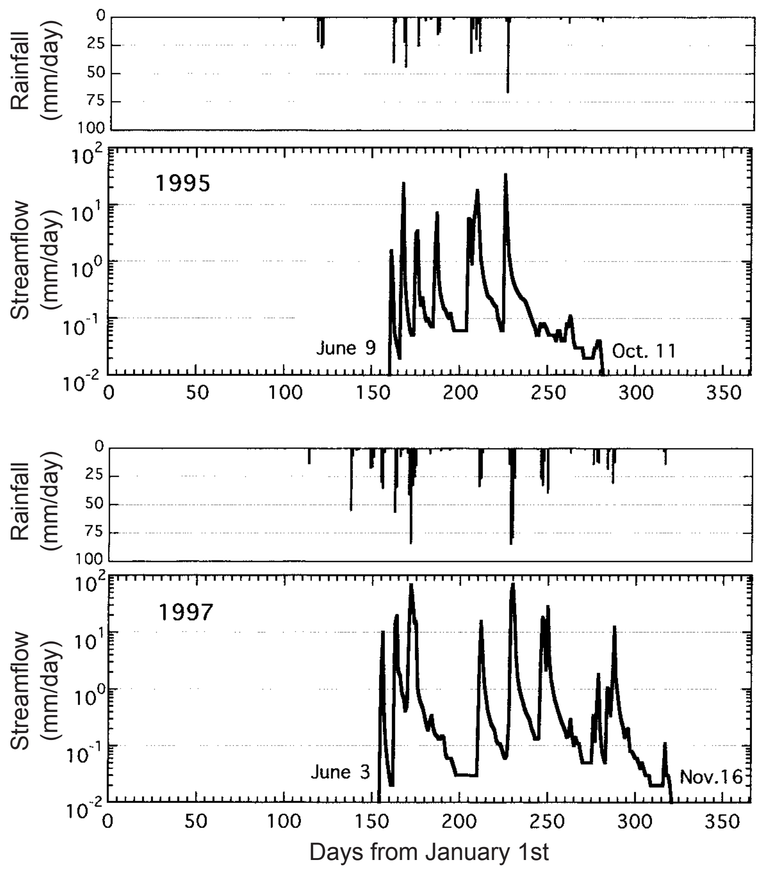


**Fig. 2. Typical annual hydrographs at the catchment**

rainfall of the catchment was estimated by the rain-gauge at the gauging station.

The rainy days (at least 0.5 mm daily rainfall) during the period varied from 16 to 61 days with a mean of 38 days per year. The maximum hourly, daily and monthly rainfalls were 23.5, 132.5 and 559.5 mm, which all occurred in June 2000. These records are equal to 2.7, 15.1 and 63.7% of annual rainfall, respectively. The maximum and minimum annual rainfalls were 1,034.5 mm in 1997 and 143.0 mm in 1998.

Assuming that annual rainfall at the Longovilo station may conform to a normal distribution, the maximum annual rainfall in 1997 is larger than magnitude $\mu + 3\alpha$ (979.9 mm), which indicates an abnormal event caused by the El Niño. The minimum annual rainfall caused by the La Niña had magnitude $\mu - 1.3\alpha$. Although streamflow in minimum year was not observed at the gauging station throughout the year, it was not as severe as the lowest annual rainfall (128.1 mm) recorded during the drought of 1968. Regression analysis indicates that the annual rainfall required to initiate streamflow may exceed 209.5 mm, which is equivalent to magnitude $\mu - \alpha$ which has occurred three times during the past 31 years at the region.

Hudson and Hazen[9] suggested that areas where the coefficient of variation of annual rainfall exceeded 0.35 had frequent droughts. Since the coefficient is 0.48, drought in this area conforms to their theory. In semi-arid regions, information on the minimum annual rainfall which adversely affects vegetation is more important than the maximum amount of rainfall.

## 2. Annual water budget and hydrological environments

Streamflow only occurs during the rainy season as an intermittent stream. Small rivers in the Cordillera de la Costa are all intermittent streams. Fig. 2 shows annual hyetograph and hydrograph of the average year in 1995 and the El Niño in 1997 at the catchment.

When the accumulated rainfall from the beginning of the water year amounted to approximately 120 mm, streamflow passed the gauging station except for the drought year of 1998. This indicates that rainfall in the early rainy season is absorbed as soil moisture storage by dry surface soils; as a result, it does not contribute to streamflow. Duration of streamflow varies from 0 to 167 days with a mean of 105 days, depending on the annual rainfall.

Table 1 shows the components of the annual water budget during the observation period. We consider that there are no catchment leaks, therefore, loss in Table 1 is equal to annual evapotranspiration (mainly evaporation from surface soils). Mean annual stormflow and baseflow amounted to 31.5% and 5.9% of mean annual rainfall. Mean annual evapotranspiration was 62.6% of mean annual rainfall.

The percentage of baseflow component to streamflow was only 15.7%. Hewlett[8] suggested that about 70% of streamflow is usually baseflow in mountainous regions of the eastern United States. The same result as Hewlett's had been obtained from subtropical forest catchments in Brazil[6]. As compared with humid forest catchments, the feature of semi-arid annual water budget may be a small baseflow component. That is, baseflow from humid mountainous catchments is usually produced from unconfined aquifers throughout the year, but baseflow from semi-arid catchments is supplied from perched aquifers only during the rainy season (see Fig. 2). In semi-arid regions, perched aquifers are frequently intermittent streams and some stormflow. Perched water tables fluctuate during wet periods and may disappear completely during the dry season[8]. The differences in aquifers affect the volume of baseflow component. This is one of the hydrological characteristics of semi-arid regions.

Examining the relationship between monthly rainfall, streamflow and evapotranspiration may help us to understand an outline of hydrological environments in the area. Monthly evapotranspiration is estimated by the following hypothesis and procedure. Potential evapotranspiration can be calculated by Hamon's equation[7] that requires only air temperature data:

$$Ep = 0.140\ D^2_0 qt \qquad (1)$$

Where Ep is potential evapotranspiration (mm/day), $D_0$ is possible hours of sunshine in units of 12 h and qt is saturated water vapour density at the daily mean temperature (g/m$^3$). Calculated annual potential evapotranspiration using the mean monthly temperature is 723.4 mm/y. Therefore, the evapotranspiration ratio is 0.49 (see Table 1). This result means that a dominant factor which controls evapotranspiration is rainfall amount and soil moisture storage.

Table 2 shows the sets of mean monthly rainfall and streamflow during the period and monthly potential evapotranspiration. The monthly potential evapotranspiration exceeds the mean monthly rainfall from October through April. It is estimated that the catchment may be under dry conditions except during the winter rainy season. In other words, vegetation may be exposed to water

**Table 1. Annual water budget at Alto Loica catchment**

| Water year | Rainfall (mm) | Stormflow (mm) | Baseflow (mm) | Streamflow (mm) | Loss (mm) |
|---|---|---|---|---|---|
| 1995 | 448.0 | 118.2 | 27.7 | 145.9 | 302.1 |
| 1996 | 314.5 | 26.8 | 10.5 | 37.3 | 277.2 |
| 1997 | 1,034.5 | 415.6 | 66.4 | 482.0 | 552.5 |
| 1998 | 143.0 | 0.0 | 0.0 | 0.0 | 143.0 |
| 1999 | 465.5 | 86.1 | 20.2 | 106.3 | 359.2 |
| 2000 | 878.5 | 355.5 | 65.8 | 421.3 | 457.2 |
| 2001 | 701.5 | 254.2 | 43.3 | 297.5 | 404.0 |
| Mean (mm) | 569.4 | 179.5 | 33.4 | 212.9 | 356.5 |
| (%) | 100.0 | 31.5 | 5.9 | 37.4 | 62.6 |

**Table 2. Mean monthly rainfall, streamflow and potential evapotranspiration**

| | Jun. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Annu. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R | 0.0 | 2.1 | 4.9 | 28.1 | 53.1 | 182.5 | 101.5 | 93.0 | 81.9 | 18.4 | 3.1 | 0.8 | 569.4 |
| S | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 73.0 | 47.4 | 48.6 | 39.0 | 4.0 | 0.0 | 0.0 | 212.9 |
| Ep | – | – | – | – | 36.4 | 27.0 | 30.7 | 30.0 | 45.0 | – | – | – | – |

R: Rainfall (mm), S: Streamflow (mm), Ep: Potential evapotranspiration (mm).
–: Potential evapotranspiration exceeds rainfall.

deficits during December through March.

We suppose that the relationship between monthly evapotranspiration (Ei) and monthly potential evapotranspiration (Epi) can be expressed by the following equation:

$$Ei = \beta Epi \quad (2)$$

Where $\beta$ is a coefficient that varies from 0 to 1 according to the soil moisture storage within the catchment. It is supposed that the period during which monthly rainfall or soil moisture storage exceeds monthly potential evapotranspiration $\beta$ may be 1. Soil moisture storage is obtained by subtracting monthly streamflow and estimated evapotranspiration from the sum of monthly rainfall and previous soil moisture storage. Although evaporation reduction is an important factor to determine evapotranspiration in the area, it is not considered there.

The same procedure is conducted on the data presented in Table 2 to help understand the soil moisture conditions at the catchment. As a result, the period of October to November $\beta$ may approximate 1. This means that the catchment may have adequate soil moisture storage to maintain evapotranspration at the potential level. Total estimated evapotranspiration from May to November amounts to 89.4% of annual evapotranspration. These results indicate that the early rainy season, May to June, is a recharge period for soil moisture storage and the early dry season, October to November, is an exhaustion period.

As the seasonal fluctuations of soil moisture storage are examined by rainfall, streamflow and estimated evapotranspiration, measurements of soil moisture are required for a better understanding of soil moisture conditions. In semi-arid regions, the most important concern of forest hydrology is not the streamflow yield, but the soil moisture conditions within the catchment, because these are the dominant factors affecting the growth of vegetation.

## 3. Characteristics of storm hydrographs

Fig. 3 shows a typical storm hydrograph at the catchment. Hydrographs which have been observed at the gauging station respond quickly to the onset and fluctuations in rainfall intensity. Moreover the hydrograph peaks are sharp and their recession segments steep. This means that a large part of the water which has fallen in the catchment directly enters streams as stormflow. As a result, a major component of annual hydrographs is stormflow (see Fig. 2 and Table 1). We observed surface detention over hillside and sheet flow on denuded and gullied areas during rainfall. Dunne[4] suggested that sheet flow occurred on grazing lands in semi-arid western North America where vegetation density is low. Judging from vegetation cover and shallow soils, storm hydrographs may be mainly formed by the saturated overland flow deriving from wetted areas around streams and the overland flow from bare land and concave hillside where sheet flow may concentrate. Hence, it appears that Horton overland flow occurs at the catchment, which contributes to sharp storm hydrographs.

Fig. 4 shows the relationship between rainfall duration ($R_D$) and stormflow duration ($S_D$). The regression equation indicates that stormflow may disappear within 10 to 20 h after the end of rainfall:

$$S_D = 9.74 + 1.16R_D \ \ (R = 0.958) \quad (3)$$

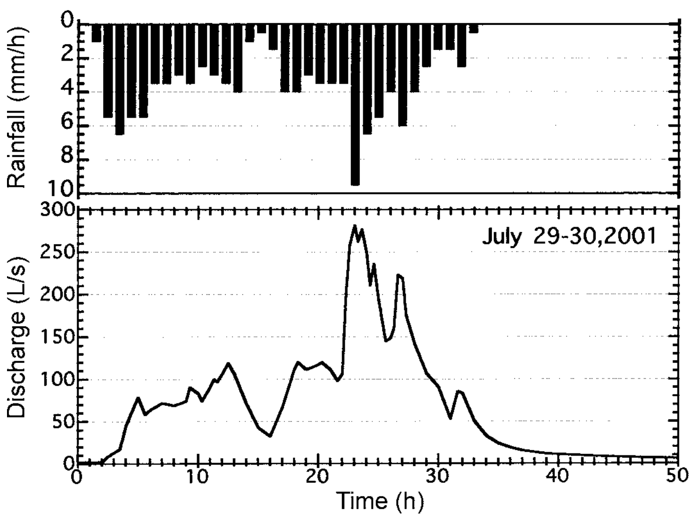


**Fig. 3. Typical storm hydrograph at the catchment**

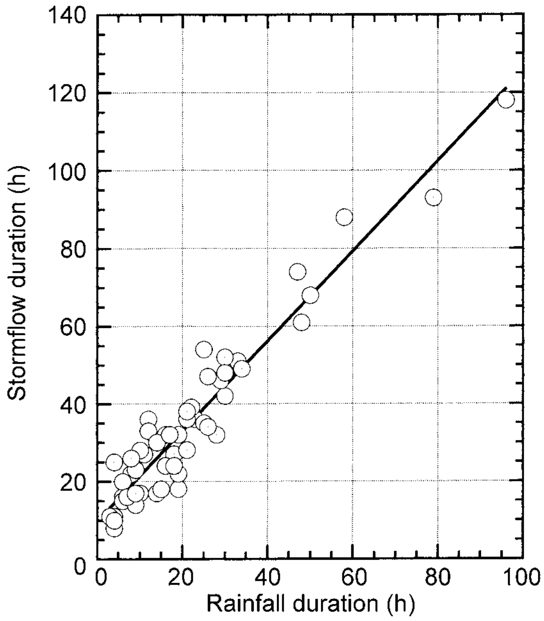


**Fig. 4. Relationship between rainfall duration and storm duration**

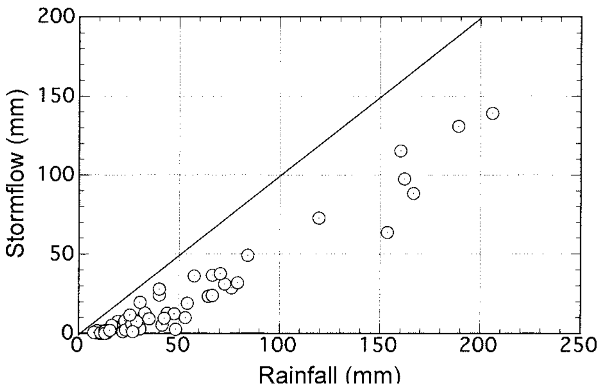


**Fig. 5. Relationship between rainfall and stormflow**

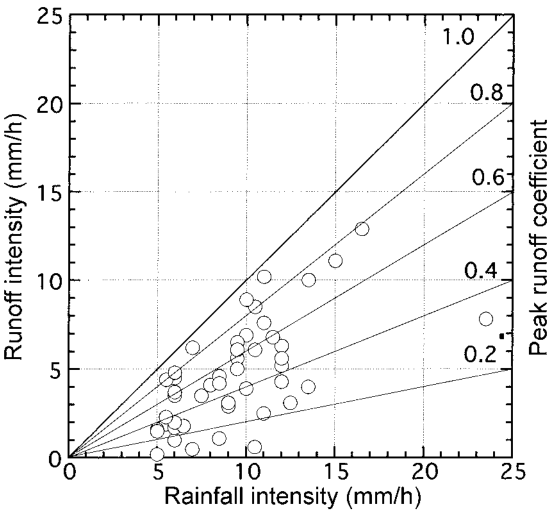


**Fig. 6. Peak runoff coefficient**

Compared with forest catchments in humid regions, the recession period of storm hydrographs, the interval from peak flow to the end of stormflow, might be short. In the case of the same catchment size, the recession period at forest catchments continued for 40 to 50 h[5]. Since subsurface stormflow is a major contributor to the recession segment at forest catchments, the recession period of forest catchments is longer than that of semi-arid hilly catchments.

The lags between the onset of rainfall and stormflow are very short. For example, lag time from maximum rainfall intensity to the hydrograph peak is less than 20 min. The observed lag time concurs with that calculated using the equation proposed by the US Department of Agriculture for hydrographs of Horton overland flow. The equation is expressed as follows:

$$Lp = 0.42A^{0.20} \quad (4)$$

Where Lp (hours) is the lag from a burst of intense rainfall to the hydrograph peak, and A is the catchment area in square km. This indicates that for catchments of less than one square km in catchment area, lag time may be less than 30 min.

Fig. 5 shows the relationship between rainfall (Ps) and stormflow (Qs). Stormflow increases linearly with rainfall amount. This means that there is a high correlation between rainfall and stormflow. The relations were approximately expressed as two straight lines:

$$0 < Ps \leq 30 \text{ mm: } Qs = -1.79 + 0.269\, Ps \ (R = 0.653) \quad (5)$$

$$30 \text{ mm} < Ps\text{: } Qs = -16.76 + 0.710\, Ps \ (R = 0.961) \quad (6)$$

Runoff coefficient (volume of stormflow / volume of rainfall) varies from 0.002 to 0.721 according to antecedent soil moisture conditions. For rainstorms of more than 50 mm, however, it ranges from 0.187 to 0.721 with a mean of 0.513. And the lower limit of the runoff coefficient increases with storm size.

Fig. 6 shows the relationship between maximum hourly rainfall intensity (at least 5.0 mm/h) and maximum hourly runoff intensity. In this figure, maximum hourly runoff intensity is not an instantaneous peak flow but the total volume of stormflow during a 60-min period included in the peak point. The peak runoff coefficient, that is, the ratio of maximum hourly rainfall intensity to maximum hourly runoff intensity, varies from 0.030 to 0.929 with a mean of 0.510. The lower limit of peak runoff coefficient increases with the rainfall intensity. Measured instantaneous peak flow during the period is 13.69 mm/h recorded September 10, 2000. It is the lower bound of the envelope curve for Horton overland flow proposed by Dunne[4], and is approximately the same

**Table 3. Saturated hydraulic conductivity**

| Soil condition | No. of measurements | Range (mm/h) | Mean (mm/h) |
|---|---|---|---|
| Grass and shrub topsoil | 18 | 16.2–216.0 | 99.7 |
| Grass and shrub subsoil | 18 | 3.9–216.0 | 58.9 |
| Bare topsoil | 12 | 2.4– 33.5 | 13.1 |

Topsoil is 4 cm deep from the soil surface. Subsoil is about 20 cm deep from the topsoil.

value as the upper envelope for variable source stormflow. It is likely that higher peak flow may be measured as more data will become available in the future.

A detailed field survey of the denuded and gullied areas within the catchment was conducted to understand the zone producing overland flow. The total area of bare land was 2.675 ha, which amounts to 16.5% of the catchment area. In addition, undisturbed soil samples were collected from grass-shrub and bare areas, and measured for saturated hydraulic conductivity at the laboratory.

Table 3 shows the results of measurement. While the mean conductivity exceeds the intensity of natural rainstorms except bare topsoil, the value is one to two orders of magnitude below that for subsurface stormflow catchments listed in Dunne[4]. The same result was obtained from a comparison of saturated hydraulic conductivities for which restoration treatments had been made[11]. These findings suggest that the permeability of semi-arid hilly catchments is lower than that of humid forest catchments. It is considered that the zone producing overland flow may be the wetted areas around streams, the bare land and the areas where soils are compacted by grazing. However, the stormflow processes cannot be clarified by the hydrological measurements and the field studies.

## Conclusion and perspective

Hydrological measurements were taken at a small hilly catchment for seven years in a semi-arid region in Chile. There was no streamflow in small rivers during drought years. Annual water budget and hydrological environments in the catchment strongly reflect the characteristics of a semi-arid climate. The most important hydrological factor for afforestation in the areas may be seasonal fluctuations in basin storage, because, this may supply us with information about soil moisture conditions which adversely affect the growth of vegetation. One conclusion that can be drawn from hydrological measurements is that native tree species which can endure severe dry seasons may be suitable for afforestation, even though Eucalyptus species have been planted there.

Horton overland flow occurs over grassy and shrub covered hillside as well as in denuded and gullied areas, and is largely responsible for sharp hydrograph peaks. During large rainstorms, mean runoff coefficient exceeds 50% of rainfall. Therefore, measures for reducing overland flow such as contour trenches, furrows on contours, check dams and bio-engineering in gullied areas, are required for both erosion control and afforestation in these regions.

Catchment experiments[13] point out that afforestation brought about streamflow reductions. Since hydrological characteristics in the region have been clarified by the project, in the future, the monitoring will be conducted with the objective to understand the influences of the growth of trees on streamflow yield and soil moisture storage in semi-arid regions.

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