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Aspects of glacial hydrology in Patagonia

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Abstract

Different aspects of Patagonian glacial hydrology are presented, by analysing hydrological statistics collected around the Patagonia Icefields. The results give preliminary estimates of specific discharges from 150 to 250 ℓ/km^{2}s in the icefield region. Studies are also made on the characteristics of seasonal variation of runoff by frequency analyses, and on the relation among the daily discharge, air temperature and precipitation in a basin of the Southern Icefield. Finally, the importance of glacial outburst floods in this area is indicated.

1. Introduction

Four large hydrographic systems originate from the Northern and Southern Patagonia Icefields (NPI and SPI) ; three drain toward the Pacific Ocean and one toward the Atlantic Ocean (See Figs. 1a and 1b). They are 1) the Baker River basin, which drains toward the southeastern side of NPI, 2) the Pascua River basin, which drains toward the northeastern side of SPI, 3) the Serrano River basin, which drains toward the southeastern side of SPI, all of which flow into the Pacific Ocean, and 4) the Santa Cruz River basin, which drains toward the eastern side of the central SPI and crosses the Argentine Pampa toward the Atlantic Ocean.

For the present study seven basins were considered : the Nef River and Colonia River basins in the Baker River basin ; Lake Viedma and Lake Argentino basins, which constitute the Santa Cruz River basin ; the Paine River and Grey River basins in the Serrano River basin ; and the Pascua River basin (see Table 1). Furthermore, a number of smaller water systems reach the Pacific Ocean directly through fjords or lakes, after flowing short distances.

Knowledge about the hydrology of these rivers, especially about water contributions from glaciers, is still very limited at the present. This is due mainly to adverse conditions for measurements, extremely harsh climate and difficulty of access to the area, very low population density with limited development, as well as the hydrographical characteristics that in most cases impede the direct measurement of the amount of water discharged from calving glaciers into fjords and lakes. All of these factors have caused a delay in the installation of an adequate hydrological control net. Up to now, systematic measurements have only been carried out with regard to a long term development program (after the year 2,000) and to exploitation of important hydroelectric potential resources in the area.

In this paper, the hydraulic features of the contributions from NPI and SPI are analysed on the basis of regular measurement data sets.

2. Analysed information

The following data were used for the analyses : hydrometric, precipitation and air temperature data collected by the Chilean Electric Company (Empresa Nacional de Electricidad : ENDESA, 1975 ; 1980) and the Water State Service (Dirección General de Aguas : DGA, 1984), and part of the hydrometric data published by the Argentine Electric Company (Agua y Energía Eléctrica : A y E, 1970). Locations of the 14 hydrometric stations and outlines of data used are shown in Figs. 1a, 1b and 2.

The catchment areas of the basins were identified by means of the following materials : 1 : 250,000 (in some areas 1 : 50,000) topographic maps published by the Instituto Geográfico Militar (IGM), trimetrogon

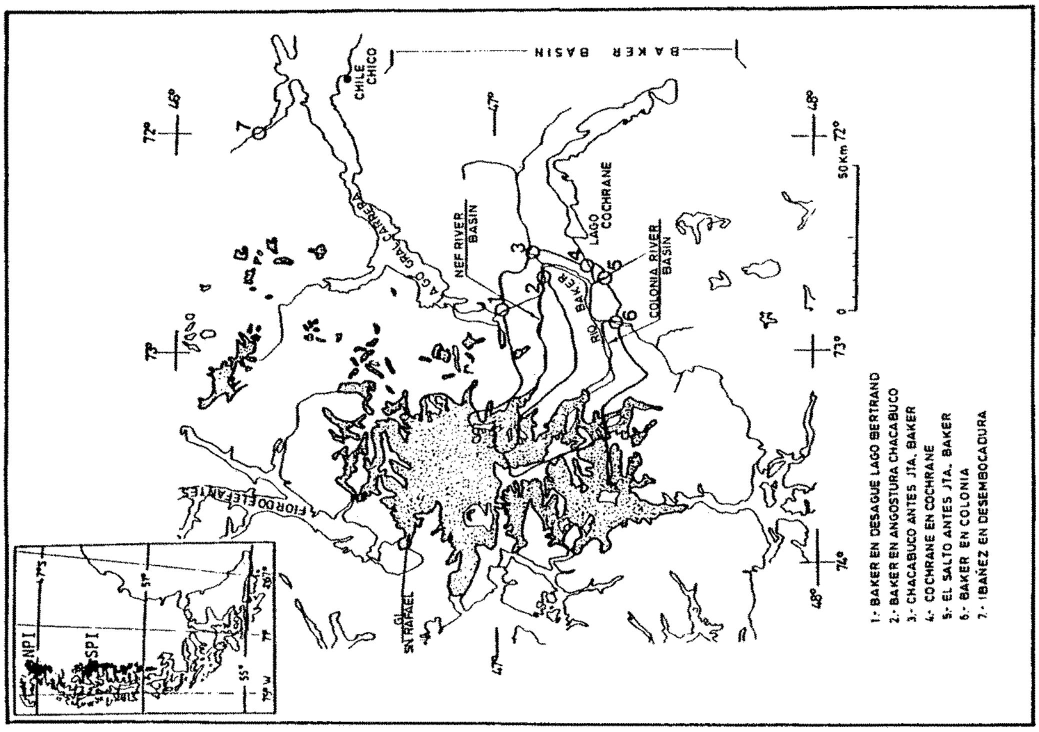

Fig. 1a. Map showing water basins in the Northern Patagonia Icefield and hydrometric stations (open circles from number 1 to 7).

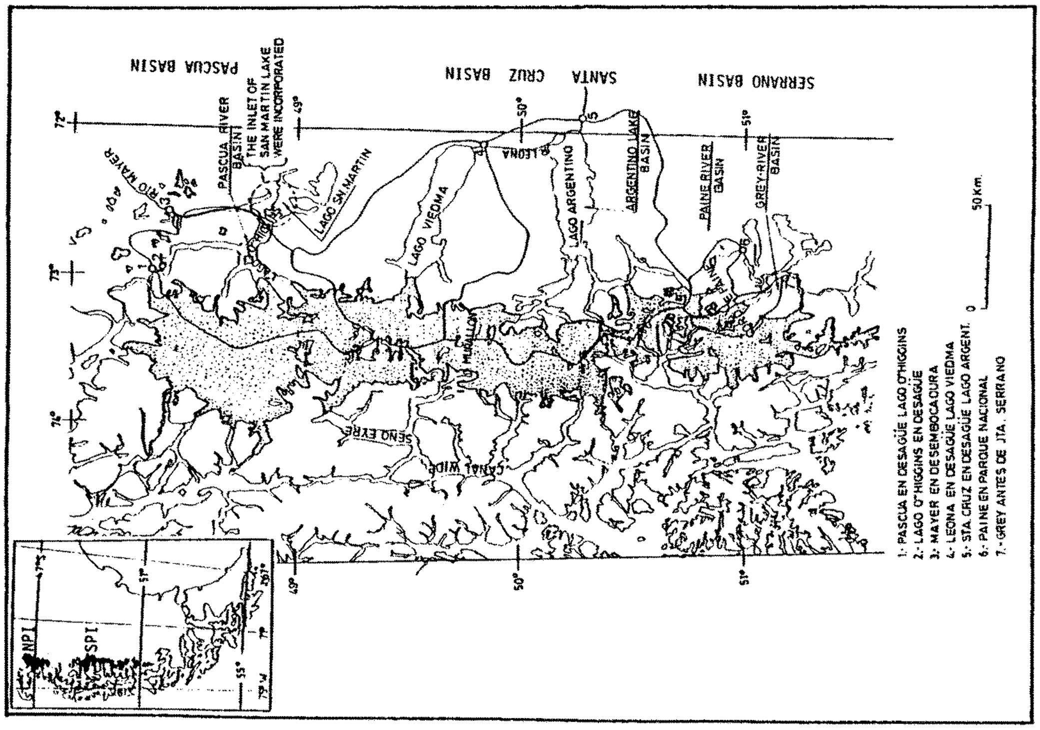

Fig. 1b. Map showing water basins in the Southern Patagonia Icefield and hydrometric stations (open circles from number 1 to 7).

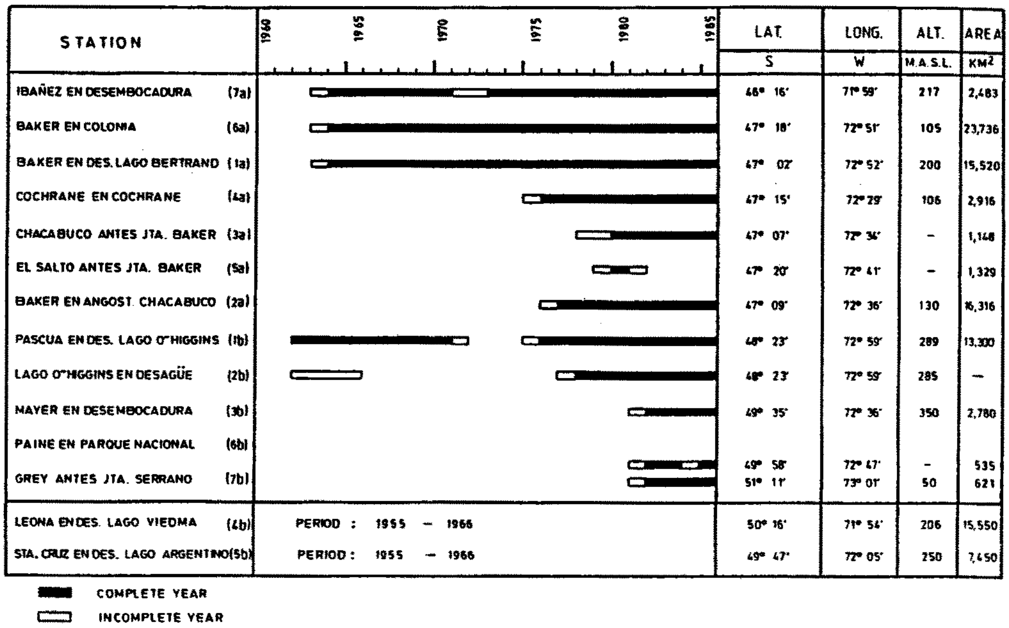

Fig. 2. Locations, altitudes, catchment areas and periods of available data at 14 hydrometric stations. Letter (a) attached to the station names indicates stations located in the Northern Patagonia Icefield area and (b) indicates those in the Southern Icefield. Stations 4b and 5b are in Argentina.

Table 1. Areas, discharges and specific discharges in each basin.
A: Total basin
B: Ice-covered and adjacent mountain areas
C: Ice-covered areas

BASIN	AREA (km^2)			DISCHARGE (m^3/s)		SPECIFIC DISCHARGE ($\ell/km^2 \cdot s$)		
	A	B	C	A	B	A	B	C
NEF RIVER	1,064	212	180	105	62	99	292	332
COLONIA RIVER	1,612	630	320	131	91	81	144	244
PASCUA RIVER	4,169	2,000	1,720	510	430	122	215	246
LAKE VIEDMA	7,450	1,218	990	266	212	36	174	198
LAKE ARGENTINO	8,100	2,090	1,530	440	401	54	192	245
PAINE RIVER	535	219	88	43	36	80	164	366
GREY RIVER	621	465	327	120	114	193	245	327

aerial photographs taken in 1944-45 and vertical photographs taken in 1974-75 by the United States Air Force (USAF), and information from Lliboutry (1956), Bertone (1960), Peña and Escobar (1983) and DGA (1984).

3. Hydrological regime and specific discharge

3. 1. Mean specific discharge

Available hydrometric data permitted the analyses of seven basins that drain large areas of the NPI and SPI (see Table 1 and Figs. 1a and 1b). However, some hydrometric stations are distant from the glacier snouts, and their drainage areas include large ice-free areas. The catchment area between a glacier snout and the corresponding hydrological control station is here termed an "interbasin" (area which is in general free of ice).

Although the specific discharge estimated for the whole area (A in Table 1) does not properly represent the specific discharge for the icefield, using information about water yield in nonglaciated areas (DGA, 1984), a discharge amount at a glacier snout was calculated (B in Table 1) by subtracting the runoff generated in the interbasin, from the discharge measured at the control station. This calculated value represents the discharge from both the icefield and adjacent mountain areas which include small-scale glaciers and ice-free areas. Finally, and only as a reference, a specific discharge for the ice-covered area in each basin was estimated (C in Table 1), assuming that runoff at the glacier front originates exclusively from the ice-covered area, thus neglecting the contribution from the ice-free adjacent mountain area.

We emphasize that the above calculated values are only a first approximation due to various error sources involved in the computations. The errors may be caused mainly by delimiting the "Divortium glatiarum" (ice divides) and water divides, and also by estimating the contributions of interbasins. With respect to the last error, it can be seen from the estimated values shown in Table 1 that the contribution of the interbasin discharge ranges from 5 % to 20 % of the total basin discharge with the exception of the Nef and Colonia River basins (contributions of 40 % and 30 %, respectively). These errors may explain such discrepancies as a very high specific discharge (B and C in Table 1) in the Nef River basin compared to a low value in the neighboring Colonia River basin.

The values shown in Table 1 suggest the following conclusions :

1) The mean specific discharges in the Patagonia Icefield region range from 150 to 250 l/km^{2}s (including the ice-covered and adjacent mountain areas, and neglecting the value for the Nef River basin).

2) If it is accepted that the annual amount of condensation and evaporation are negligible compared to the annual precipitation, a mean equivalent annual precipitation of 4,800 to 7,900 mm/a is obtained as an average in the ablation and accumulation areas. This suggests that an equivalent annual precipitation may be greater than 8,000 mm/a in the accumulation area of the icefields.

3. 2. Seasonal variation of runoff : Frequency analysis

Frequency analysis of seasonal variations of runoff is first made for the Pascua River basin in SPI. We use the discharge data at the Pascua River station near the outlet of Lake O'Higgins and also the water-level records at the lake. These have the following two advantages :

1) A large proportion of the measured discharge at the Pascua River comes from ice-covered areas and adjacent mountain areas (84 %, see Table 1).

2) A long term record of lake-level fluctuations is available for Lake O'Higgins and the regulating effect (change in the stored water) of the lake can be eliminated by using this record and the outlet discharge at the Pascua River. In fact we are interested in discharge data of the input rivers to the lake, which drain mostly water from glacial areas. Since this information is not available, we may use the discharge data of the outlet Pascua River and add (or subtract) the stored (or released) water volume in Lake O' Higgins throughout the year, obtaining this way a new discharge value which we shall name "Natural Discharge" (N. D.). This value represents the input discharge to the lake.

Figure 3 shows obtained seasonal variation of natural discharge (N. D.) at the Pascua River, together with the measured discharge at the river, and monthly

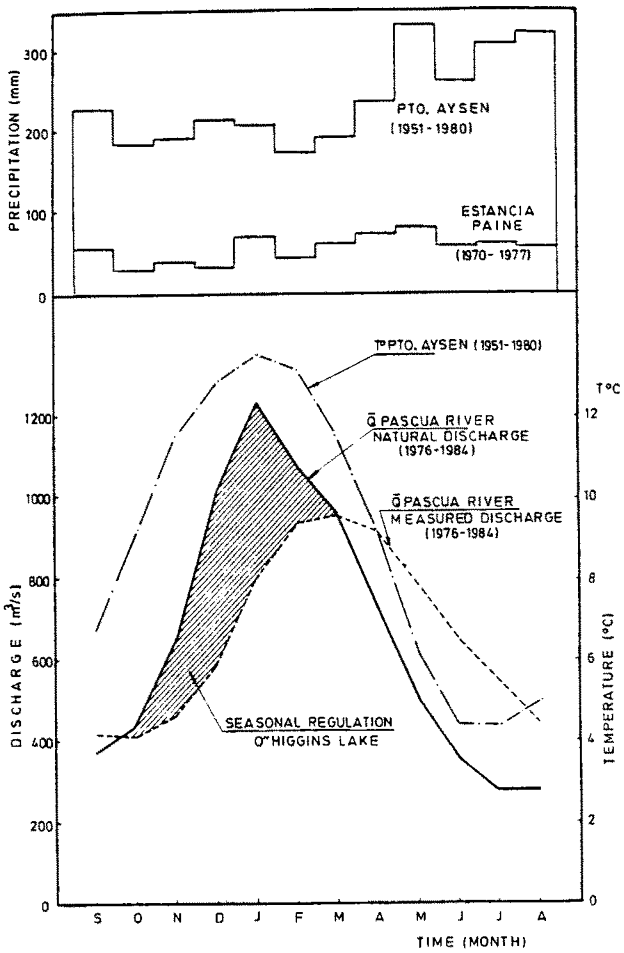

Fig. 3. Seasonal distributions of the monthly mean discharges (measured and natural discharges) from the Pascua River, and comparison of them with air temperature and precipitation in Puerto Aisén, and precipitation in Estancia Paine.

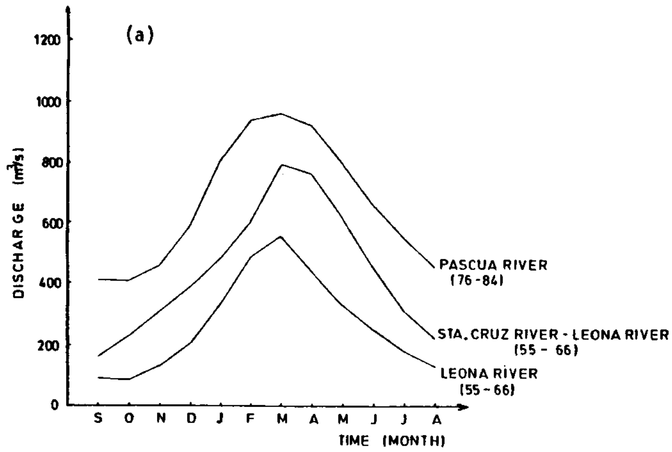

Fig. 4a. Seasonal distribution of the monthly mean discharges at three basins in the Southern Patagonia Icefield, each regulated by its respective lake.

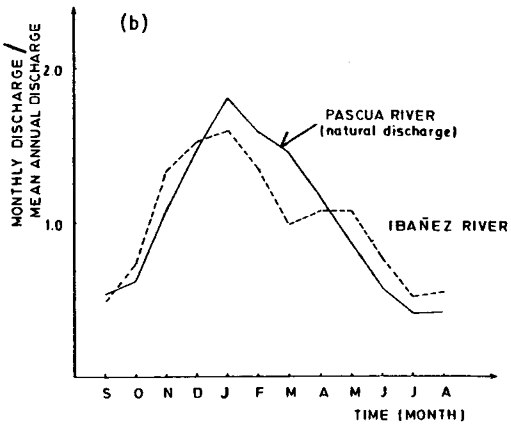

Fig. 4b. Seasonal distribution of relative discharges (*i.e.* the monthly mean discharge divided by the annual mean discharge) at the Pascua River (natural discharge), which has a strong glacial influence, and at the Ibañez River, which has a weak glacial influence.

mean air temperature and precipitation at Puerto Aisén in northern Patagonia. Values of N. D. indicate a typical discharge of glacial origin, with a clear seasonal fluctuation. The maximum discharge occurs in January, with a specific discharge of the ice-covered and adjacent mountain areas of about 400 ℓ/km^2s, which is about 4.5 times higher than the winter discharge. This seasonal variation in discharge is thus closely related to the temperature variation, and as can be seen from Fig. 3, it seems to be independent of the precipitation variation which does not show a regular seasonal change. When the seasonal distribution of discharge in the different rivers which drain from the Patagonia Icefields are compared, all of them show similar features having their peaks in summer and minimum values in winter (see Fig. 4a). On the other hand, this pattern is notably different from the one observed in other rivers of the area with small glacial influence, such as the Ibañez River (Station No. 7 in Fig. 1a). The discharge of the Ibañez River was analysed (Fig. 4b), and it shows a secondary maximum in May, probably due to the precipitation. The January discharge for this river is about three times higher than the discharge in winter.

Frequency analysis was carried out for both the Pascua and Ibañez Rivers, using the following method :

At first the monthly discharges for the observation period (9 years for the Pascua River and 23 years for the Ibañez River) were ordered for each month from the smaller value (Q_{min}) to the larger (Q_{max}).

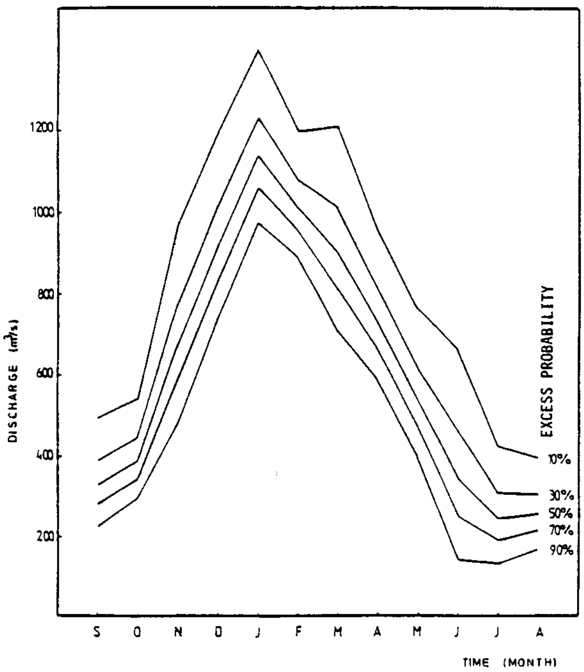

Fig. 5. Seasonal variation curves of the monthly mean discharge (natural discharge) with each excess probability at the Pascua River.

According to the order number an excess probability was assigned to each value. The highest order discharge was given an excess probability near to 0 %, while the lowest order one was given one near to 100 %. Thus the probability of having a monthly discharge in excess of the lowest value recorded during the observation period, *i.e.* excess probability, is near to 100 %.

The seasonal variations of discharge for various excess probabilities were calculated for the two rivers, and their curves are illustrated in Figs. 5 and 6. Also the standard deviation (σ) of the monthly discharges (Q) and other parameters are tabulated in Tables 2 and 3.

The result of the above analysis for the Pascua River, which has a strong glacial influence, shows relatively constant values of the standard deviation throughout the year. It results in almost parallel seasonal variation curves for different excess probabilities (Fig. 5, Table 2), whereas the result for the Ibañez River, with a weak glacial influence, shows greater variability and presents seasonal trends in the standard deviation (Fig. 6, Table 3). In this case the seasonal variation curves for higher excess probabilities tend to be similar to those corresponding to basins with large ice covered areas, that is, they have only one annual peak in January.

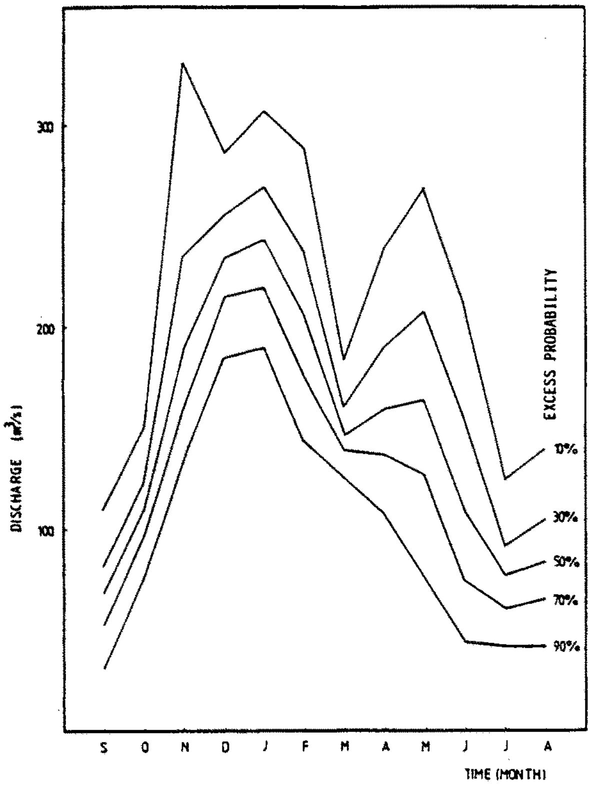

Fig. 6. Seasonal variation curves of the monthly mean discharge with each excess probability at the Ibañez River.

4. Relationship among discharges and meteorological variables

An important feature of long and short term fluctuations of the Patagonian ice masses is consi-

Table 2. Frequency analysis for the Pascua River (natural discharge).
Q: Mean of the monthly mean discharge
$\bar{Q}$: Mean of the annual mean discharge
Q_{min}: Minimum value of the monthly mean discharge
Q_{max}: Maximum value of the monthly mean discharge
σ : Standard deviation of the monthly mean discharge
C_v : σ/Q

MONTH	Q m³/s	σ m³/s	C_v	Q_{min} m³/s	Q_{max} m³/s	$Q/\bar{Q}$
JANUARY	1167	179	0.15	835	1564	1.81
FEBRUARY	1028	127	0.12	767	1233	1.59
MARCH	933	212	0.23	457	1186	1.45
APRIL	755	154	0.20	478	1102	1.17
MAY	562	154	0.27	364	854	0.87
JUNE	377	217	0.58	147	811	0.58
JULY	262	122	0.47	87	520	0.41
AUGUST	269	94	0.35	154	413	0.42
SEPTEMBER	343	112	0.33	172	542	0.53
OCTOBER	403	104	0.26	264	683	0.62
NOVEMBER	698	203	0.29	224	1062	1.08
DECEMBER	945	190	0.20	683	1255	1.47
ANNUAL VALUE	645	69	0.11	543	825	1.00

Table 3. Frequency analysis for the Ibañez River.
Same column headings as Table 2.

MONTH	Q m³/s	σ m³/s	C_v	Q_{min} m³/s	Q_{max} m³/s	$Q/\bar{Q}$
JANUARY	251	50	0.20	411	160	1.60
FEBRUARY	212	50	0.23	329	121	1.35
MARCH	155	23	0.15	213	102	0.99
APRIL	169	54	0.32	345	76	1.08
MAY	170	69	0.41	356	47	1.08
JUNE	121	67	0.55	298	17	0.77
JULY	82	38	0.47	208	28	0.52
AUGUST	86	34	0.39	162	13	0.55
SEPTEMBER	76	37	0.49	191	12	0.48
OCTOBER	115	34	0.29	235	43	0.73
NOVEMBER	211	75	0.36	454	105	1.34
DECEMBER	240	41	0.17	351	156	1.53
ANNUAL VALUE	157	23	0.15	201	104	1.00

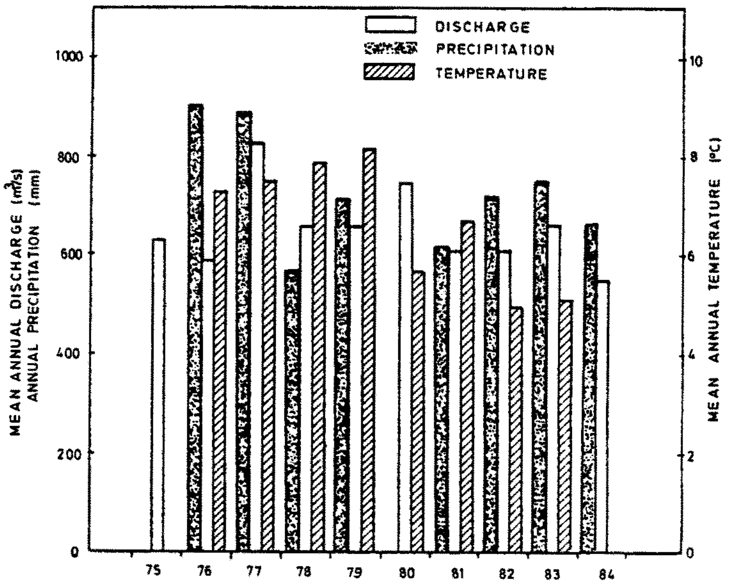

Fig. 7. Annual variations in the annual mean discharge (natural discharge) of the Pascua River, and the annual mean air temperature and annual precipitation at Tenencia Lake O'Higgins station, from 1975 to 1984.

dered to be caused by the fluctuations of meteorological variables. This is also of great interest in practical hydrology such as runoff forecasting, resource evaluation, flood calculations, *etc.*

Figure 7 shows variations in the annual mean discharge (N. D.) at the Pascua River, the annual precipitation and the annual mean air temperature. We cannot find clear relations between the discharge and the precipitation/temperature. The period of available data might be too short to be able to draw definite conclusions.

The analysis of daily discharges was carried out for the Grey River (Station 7b) and shows a fairly good correlation between the daily mean temperature and the discharge in the preceding day, as shown in Fig. 8. To clarify this tendency, correlation analyses were made for the spring to summer period of 1982-83, among the daily discharge, the daily mean temperature, and daily precipitation. The results are listed in Table 4. Two regression equations, which have high correlation coefficients, are shown in the table. It is necessary to notice, however, that these

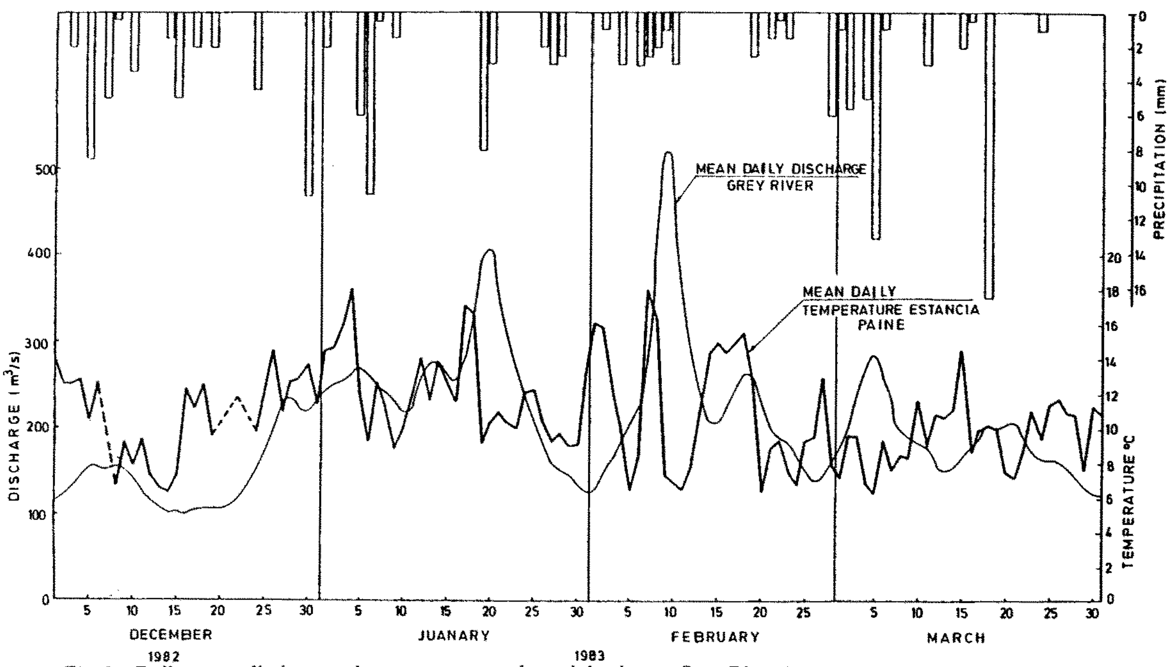

Fig. 8. Daily mean discharge, air temperature and precipitation at Grey River basin, from December 1982 to March 1983.

Table 4. Relationship among the daily amount of discharge (Q), the daily mean air temperature (T) and the daily amount of precipitation (P) at the Grey River basin. The subscript 'i' indicates a day. The best-fitted linear regressions with two or three independent variables are:

REGRESSION (3): $Q_i = 0.913\, Q_{i-1} + 5.16[(T_{i-1}) - 7.4]$

REGRESSION (6): $Q_i = 0.902\, Q_{i-1} + 2.47\, P_{i-1} + 5.42[(T_{i-1}) - 7.7]$

REGRESSION No.	INDEPENDENT VARIABLE	CORRELATION COEFFICIENT
1	Q_{i-1}	0.929
2	Q_{i-1}, T_i	0.936
3	Q_{i-1}, T_{i-1}	0.949
4	Q_{i-1}, P_i	0.933
5	Q_{i-1}, P_{i-1}	0.931
6	Q_{i-1}, T_{i-1}, P_{i-1}	0.952
7	Q_{i-1}, T_i, T_{i-1}, P_{i-1}	0.952
8	Q_{i-1}, T_{i-1}, T_{i-2}, P_{i-1}	0.952

results over-evaluate the influence of the preceding day's discharge due to the regulation effect of the lakes located upstream of the measurement point. It is noted that the daily discharge seems to depend strongly on the preceding day's temperature (T_{i-1}).

5. Outburst floods of glacial origin

Several sudden floods of glacial origin in the Patagonia Icefields have been reported and studied. The best known cases are Moreno Glacier (Lliboutry, 1956 ; Liss, 1970), Colonia Glacier (Lliboutry, 1956) and Dickson Glacier (Peña and Escobar, 1983). Considering the great extension of the ice-covered areas and the existence of large lakes at the glacier snouts which produce an important regulation effect, it is possible to suppose that this phenomenon might be an important and not infrequent characteristic of the region.

There are some conditions in the Patagonia Icefields that contribute to the generation of an outburst flood. These are :

1) The existence of vast flat areas on the icefields, partly surrounded by mountains, can lead to

large water storage and the development of important supraglacial lakes, as in the case of Dickson Glacier.

2) High melting rates of ice and much precipitation permit the presence of large water storage on/within glaciers.

3) The periodical fluctuations of some glaciers (such as Moreno Glacier) make it possible to block a stream with an advancing glacial tongue and to originate a glacier dammed lake.

This aspect of glacial hydrology in Patagonia should be investigated because of its importance for future development of the regional water resources.

Acknowledgments

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Resumen

Aspectos de hidrología glacial en la región Patagónica

En este estudio se presentan diferentes aspectos relativos a la hidrología glacial de la Región Patagónica, basándose fundamentalmente en estadísticas hidrológicas recolectadas por los Servicios Estatales Chilenos y Argentinos, e información del rendimiento hídrico de las áreas próximas a los Hielos Patagónicos Norte y Sur (Balance Hidrológico Nacional, Chile, DGA, 1984). Desde estos campos de hielo se originan cuatro grandes sistemas hidrográficos : las cuencas del Río Baker, Pascua y Serrano que descargan en el Océano Pacífico, y la cuenca del Río Santa Cruz que descarga en el Oceáno Atlántico, habiéndose incluído en el estudio información de 7 subcuencas de estos sistemas.

El análisis efectuado permitió hacer una estimación de los caudales específicos de las áreas con hielo y una caracterización de la variación estacional de estas descargas. El caudal específico medio en la zona de los Hielos Patagónicos, de acuerdo al estudio, fluctúa entre 150 y 250 ℓ/km^2s lo que equivale a valores de precipitación anual media de 4.800 a 7.900 mm/año como promedio para las zonas de acumulación y ablación. Considerando las precipitaciones medidas en los alrededores del campo de hielo, y los antecedentes presentados, se estiman valores de precipitación superiores a 8.000 mm/año para la zona de acumulación. En cuanto a la distribución estacional de los caudales, se efectuó un análisis de frecuencia de la información mensual del Río Pascua en régimen natural (N. D.). Dicho análisis entrega caudales máximos en Enero con valores medios de aproximadamente $400\ell/km^2s$, el cual es 4, 5 veces mayor que el caudal de invierno. La distribución estacional del caudal en los diferentes ríos que drenan los Hielos Patagónicos es similar, mostrando una estrecha relación con la variación estacional de la temperatura, no así otros ríos de la región con menor influencia glacial, los cuales presentan un máximo secundario en Mayo.

Además, se analizó la relación entre el caudal, la temperatura del aire y la precipitación, tanto a nivel anual como diario. A nivel anual, se observó una gran independencia entre las variables, aunque la longitud de los registros no permite deducir conclusiones definitivas. A nivel diario, el análisis de correlaciones muestra una fuerte dependencia del caudal de un día con el correspondiente al del día anterior y con la temperatura diaria, y una relativa independencia con la precipitación.

Finalmente, se destaca la importancia de las crecidas por vaciamiento violento de lagunas glaciares en la región (Jökulhlaup) y las caracte rísticas propias de la zona que favorecen dicho fenómeno.