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# Preliminary hydrological results from Sarennes glacier basin, French Alps

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## ABSTRACT

Located in the French Alps, Glacier de Sarennes is a small glacier which has its mass balance, measured since 1948.

Now since 1992, the Snow Engineering and Avalanche control department of Cemagref Grenoble measures water level in the emissary of this glacier at the altitude of 2800 meters. The time step of these records is 10 minutes. The aim of this study is to realize the first hydrological assessment, despite having few records until now, to be able to control the new experimental discharge station, and to extract the first scientific results.

## INTRODUCTION

The E.R.Bs. *(European Research Basins)* represent excellent tools for hydrologists: real open air often of small size, they offer powerful means to observe the water cycle and its processes *(Barbet D., Givone P., 1992)*. The Sarennes E.R.B., one of the recent French E.R.B.s, presents two special particularities:

- the length of some data: more than forty years for annual glacier balance *(Valla F., 1989)*.
- its specificity: the only French glacierized E.R.B.

This glacier located in the French Alps (30 km east south-east from Grenoble), at the northern border of the French Oisans massif, is studied for the mass balance since 1948, firstly by the "Eaux et Forêts" Service (De Crecy L., 1963), and now by the Snow Engineering and Avalanche control Department of Cemagref Grenoble (Valla F., 1994).

This very long set of data interested the glaciologists, who used it to strictly study this glacier, but also for the general typology of alpine glaciers, the relations between meteorological variables (precipitations, temperatures) *(Martin S., 1977)*, and the discharge forecasts for hydroelectric power generation *(Braun L.N. & al., 1993)*.

The Snow Engineering and Avalanche Control Department from *Cemagref* Grenoble satisfied the hydrologists, installing in 1992 a gauging site near the glacier outlet, on the Sarennes river *(Valla F. & al., 1993 –Tairraz V., 1992)*. The precipitation measurement was improved (with financial help from *E.D.F.-D.T.G. : Elecricitè de France– Direction Technique Gènèrale*), with telemetry of snow cover (daily time step, rain recorder). The aim of this study is to treat the first runoff data sets (1992, 1993, and the beginning of 1994), and to extract also the first hydrological results *(Barbet D., 1994)*.

Three different aspects are examined :
- Firstly an overview of the mass balance data set, and the main results about it.
- Secondly how the water depths are obtained in a mountainous basin, with metrological difficulties, and how discharge set data are issued from these data, how the missing data are filled in for the discharge set by multilinear regression between meteorological va-

riables. This aspect is concluded by a description of the Sarennes typology, with several time steps: annual discharge values, monthly discharge values (seasonal variations), daily discharge values (mean, instantaneous maximum, instantaneous minimum) and finally hourly discharge values (daily fluctuations), with also the description of some historical representative data sets during the melt period, and the study of the relation discharge-temperature with a hourly time-step. Finally the discharges-durations curves are constructed for the two complete years, and an estimation of the flood characteristic duration is also given.
Thirdly the correlation between discharge and meteorological parameters, with a 0 to 5 days lag was studied.

## THE SARENNES GLACIER MASS BALANCE SINCE 1948

The Sarennes Glacier covers an area about 0.57 km² for a total area of 1.38 km² at the gauging station (see figure 1). Its coordinates are 45°07' N, 06°08' E. The elevation is between 3327 m. and 2800 m. The access is now easy from the top of Pic du Lac Blanc (top of the basin), using the highest cableway of the ski area known as l''*Alpe d'Huez*.

The main characteristics of this little glacier are :

- a South exposition. Sarennes is a relic of the last glacial extension.

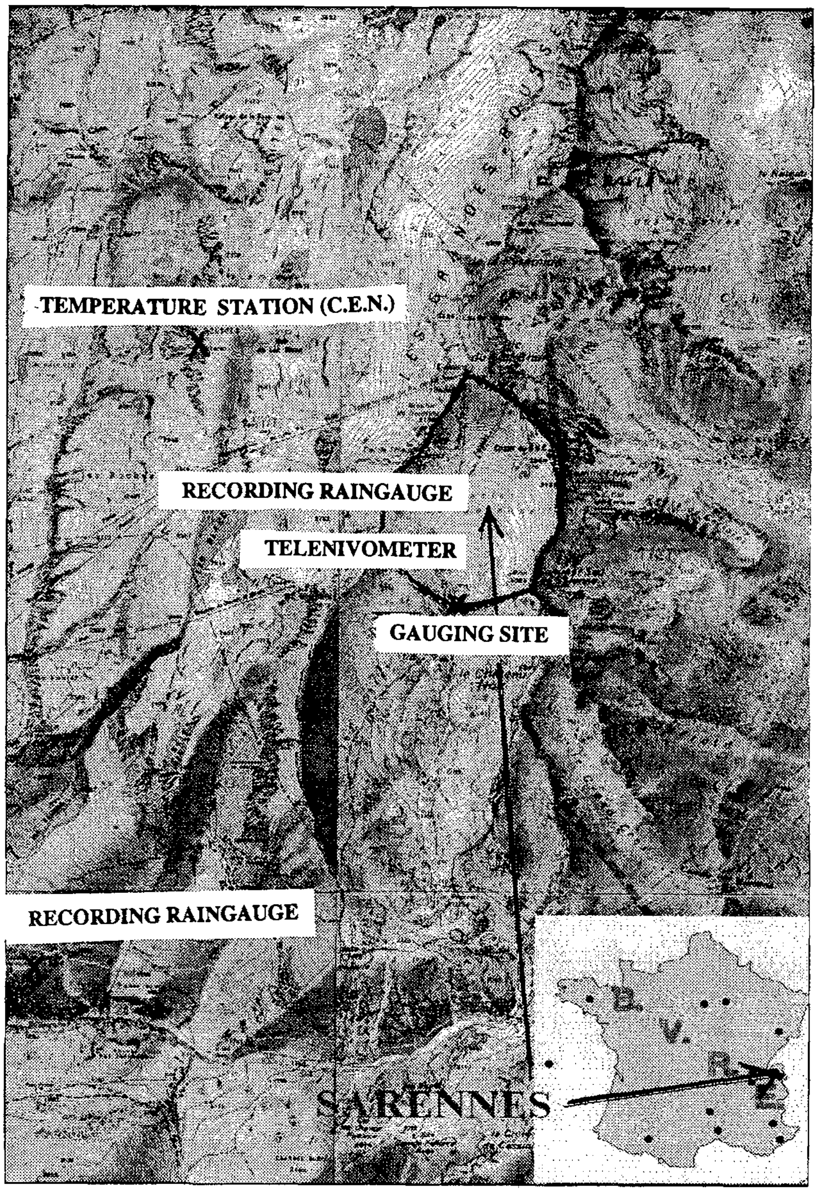



Figure 1. Situation map of the Sarennes glacier.

- a lack of movement as the oscillations are strictly vertical.
- a constant decrease of the glacierized area :
  - 1.09 km² in 1909.
  - 0.70 km² in 1981.
  - 0.57 km² in 1992.

*Some historical data.*

Despite of its small size, Glacier de Sarennes is known for at least one century. The first recorded visit was in 1891 by Prince Roland Bonaparte, a relative of Emperor Napoleon. He noted that the glacier front was more or less stationary. Fifteen years later, in 1905-1906, three researchers of the Grenoble University conducted important scientific works mainly in glaciology in the Oisans massif. They surveyed the glacier and drew a map at the scale of 1/10 000 with a high accuracy. The first photographs of Sarennes were taken in 1905 attesting the good health of the glacier. After that the Ministry of Agriculture financed several campaigns because the ministry well understood the fundamental role of glaciers in the hydrological behaviour of the alpine streams. As a result observations and data collections were made by the organization called "Eaux et Forêts", now relayed by *Cemagref*. Some photographs and locations of the glacier's front were published in 1927 and 1933.

*45 years of mass balance.*

With its lack of movement, this glacier is considered as a gigantic raingauge that stores the snow precipitation. Since 1948, four main parameters are measured: accumulation, ablation, mass balance and regime. The mass balance is the difference between accumulation and ablation, the regime is the sum of accumulation and ablation. The figure 2 presents the cumulated mass balance of the glacier since 1948. The graph shows a loss of 30 meters of water equivalent in 45 years, which corresponds to a mean annual rate of 0.66 meter of water equivalent. Because of the lack of significant movement of the ice of the glacier de Sarennes, figure 2 gives an idea of the variation of the ice level at the elevation of about 3000 m. In the center part of the glacier, the loss of ice is roughly 34 meters ( = 30 m. / 0.9 ; 0.9 is the ice density.) *(Funk M. & al., 1993).*

FROM WATER DEPTH TO DAILY DISCHARGES.

At an elevation of 2800 m. a gauging station was built in 1992, to measure water level data.
The basin area covers 1.38 km², of which 0.57 km² glacierized. The water level is measured with two different probes: a capacitive water level probe, and an hydrostatic water level probe, in a rectangular measuring weir. The water level is observed at intervals of 10 minutes.

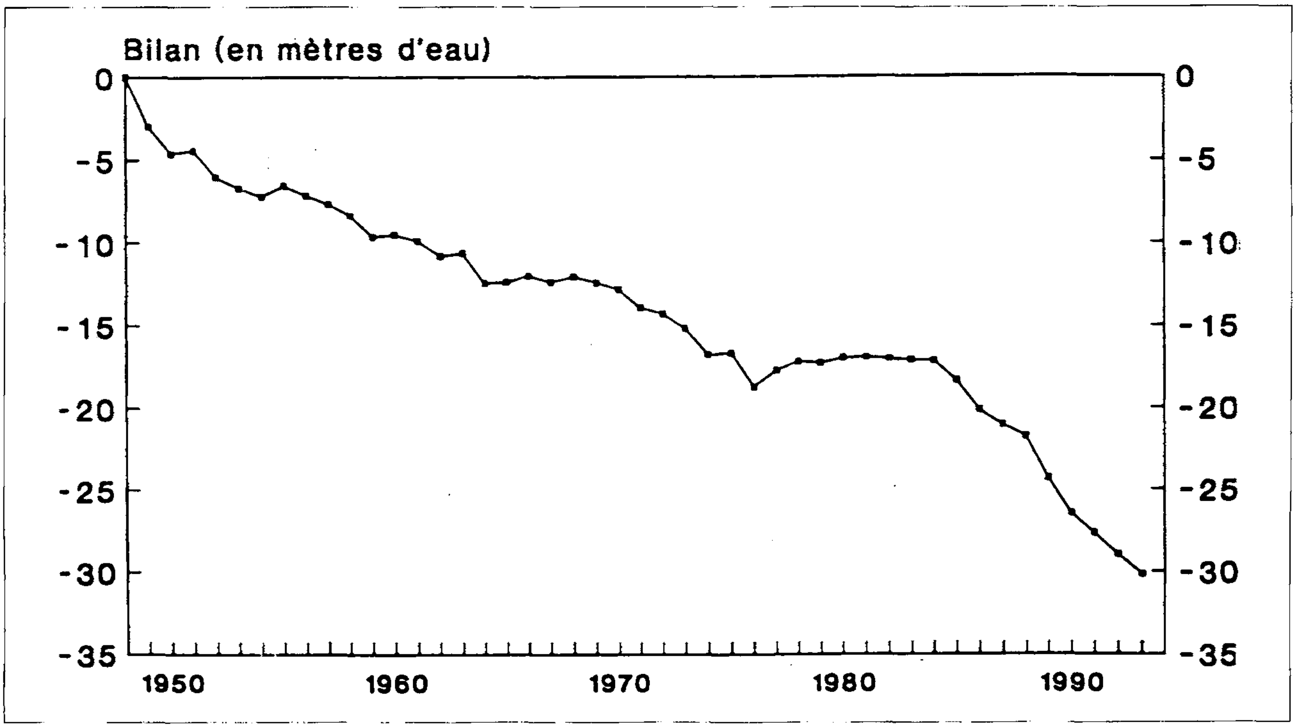



Figure 2. Accumulated mass balance on Sarennes Glacier since 1948.

*Hydrometrical problems and their solutions.*

An important part of this work was to solve several metrological and hydrometrical observation problems. But these problems were specific to this station: water depth beyond the measures range of the principal probe; differences between the measured depths for the gauging (dilution gauging or velocity-area method) and by the probes, water over the weir for some summer floods... We bypassed successfully the difficulties with classical calculation methods: linear regression, hydraulic classical formulas. A good rating curve was finally

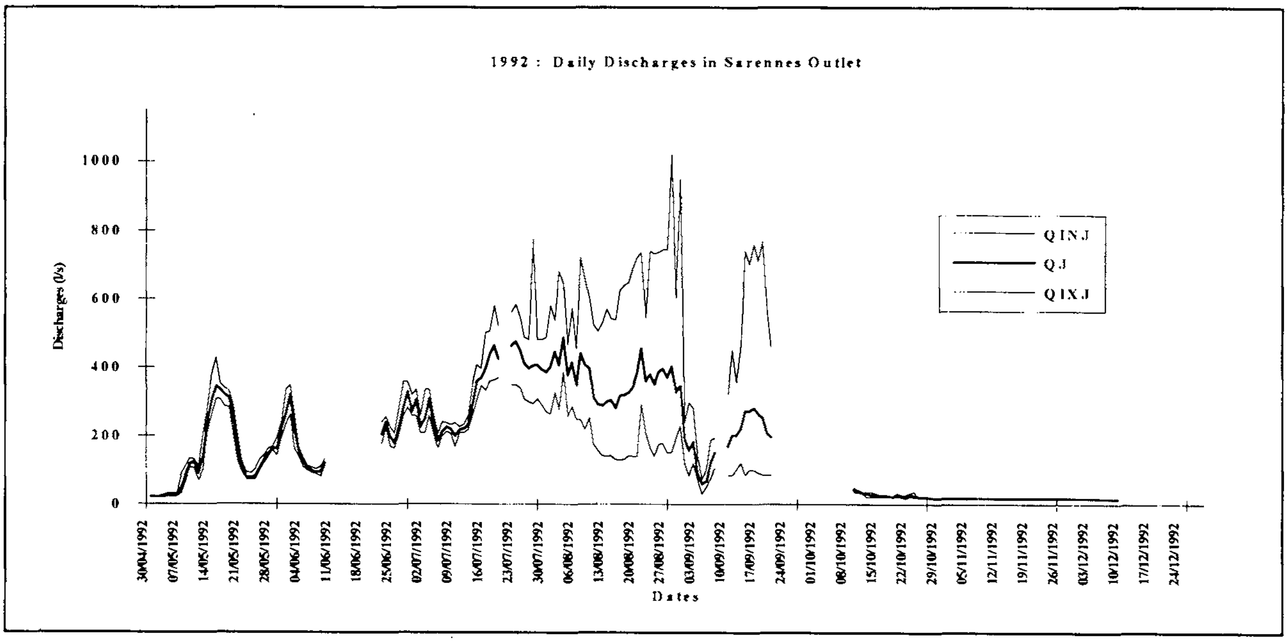



Figure 3. Annual discharge hydrograph (QJ, QIXJ, QINJ): year 1992.

obtained, for the period of the study (1992-1994). Then we could build the discharge year book for different values: daily discharge (called **QJ**), instantaneous maximal discharge for one day (called **QIXJ**), instantaneous minimal discharge for one day (called **QINJ**), the annual discharge, the monthly discharges, and the corresponding graphs. The figure 3 gives the discharge hydrographs (QJ, QINJ, QIXJ) for the year 1992.

*Filling in the daily discharge blanks.*

Because of a very difficult access (high elevation, snow, no pathway), some days of the years 1992 and 1993 were missing. An interesting part of the study was to fill in missing daily discharge. The method used *(Lang H. & al., 1985)* was an ascending (choice by Student T) multilinear regression between discharge and available meteorological variables (daily temperature and daily precipitations), with a 0 to 5 days lag, adjusted only for the deficient period (with around 15 days before and 15 days after). An example of the results obtained is shown in the figures 4 and 5 for the missing period of June 1992.

The correlation coefficient is equal to **0.89**. The regression equation is:

$$QJ = 136.9+22.6T_{J1} + 0.189P_{J1} + 9.49T_{J4} + j$$

(only for June 1992)

with :
QJ = Daily discharge for the day J.
TJ1 = daily temperature for the day J-1.
PJ1 = daily precipitation for the day J-1.
TJ4 = daily temperature for the day J-4.
φ = residual error

The parameters in the regression equation give some explanation about the hydrological behaviour of this glacier at the beginning of the melt period : in june, the snow cover is still strongly present, the runoff durations are low. Thus the precipitation and the temperature of the day J are not included in the equation. On the other hand, the concentration time between a rainfall event and its runoff seems to be equal to 24 hours (presence of the PJ1 parameter).

For the TJ4 parameter, it is more difficult to explain its signifiance. The recurrence interval between two atmospheric disturbances is roughly equal to four days. These disturbances would máke the temperature goes down. This TJ4 parameter is probably not stable, and would disappear in a more general model.

In conclusion filling in this missing period, we find here a strong relation with temperature: the daily discharges decrease considerably when the temperature becomes negative.

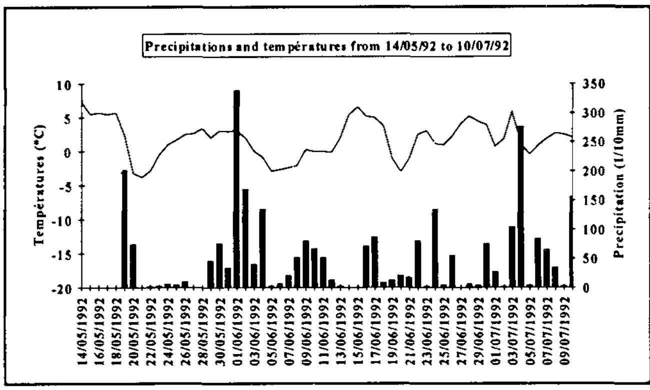



Figure 4. Daily precipitations and daily temperatures for the period of june 1992

All the missing periods were filled in with the same approach and the same success (good correlation coefficients), but with other parameters following the different periods of the melt season.

To improve the results, the use of a third radiation parameter would seem a good choice in the future.

## TYPOLOGY OF THE SARENNES RIVER: A GLACIAL RUNOFF REGIME.

After filling in the discharges blanks, the hydrological behaviour of this glacier is studied. We will precise it with its typology.

*The other meteorological variables.*

To build the typology of the Sarennes Glacier, meteorological variables are needed. In this study, data from the nearest stations were used.

For the precipitation values, the *Alpe d'Huez* (altiport) station –1860 m.–, with a daily time step records, was chosen. For the temperatures, the *Dôme des Petites Rousses* station, with an hourly time step records was taken. The particularity of this station (*C.E.N. Grenoble*) is that observed values from november to april, and calculated values for the other part of the year (*SAFRAN* Model) were available *(Durand Y., E. Brun & al., 1993)*. The figures 6 and 7 give daily values for temperature and precipitations for the year 1992.

*The annual values.*

The average values of the meteorological variables are shown in the table 1 for the two years of the study

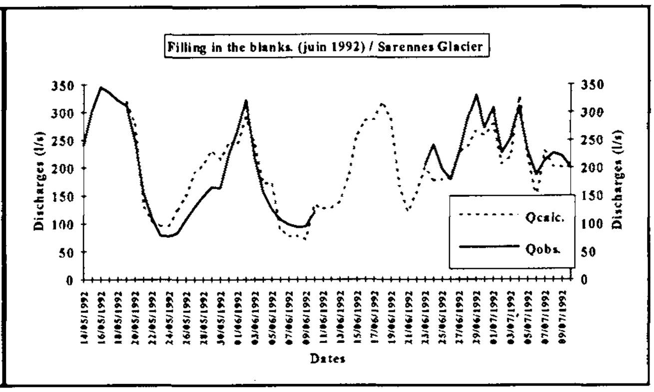



Figure 5. Observed daily discharges and calculated daily discharges: lacunal period of june 1992.

(1992 and 1993).

These values can be compared with some representative French glaciary rivers (Gaudet F, 1973) :

These values show that the Sarennes river has a specific discharge similar to rivers with a comparable rate of glacierized area (the scale effect disappears here with the specific discharge). It can be concluded that these specific discharges are high: the one of the Seine in PARIS is equal to 6.1 l/s/km≤ (interannual modulus).
The high values for Sarennes and the glaciary rivers resulted from :

- the elevation, that involves strong precipitations.
- the low temperatures, that involve a low evaporation.

*The flow duration curve.*

The flow duration curve is given in figure 8 for the two years of the study.
From the observations of these curves, it can be noticed that :

- the discharge values that are very low have a duration equal to six months for the two years. They are the low flows of the winter period, depending on the temperature and very regular from one year to another.
- The maximum daily discharges, exceeded less than

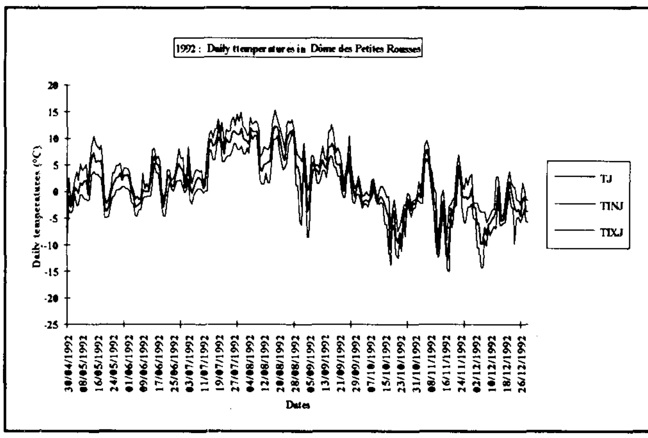



Figure 6. Daily temperatures: year 1992

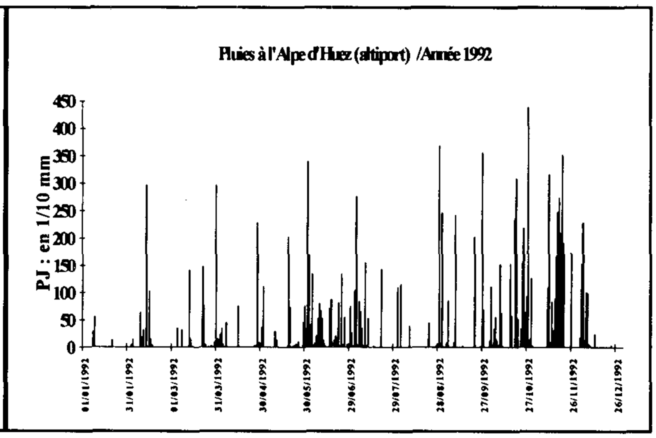



Figure 7. Daily precipitations : year 1992

**Table 1. Some characteristic values of the meteorological variables.**

| | 1992 | 1993 |
|---|---|---|
| annual depth of runoff (mm) | **2473** | **1854** |
| annual discharge (l/s) | **108** | **81** |
| specific discharge (l/s/km²) | **78.2** | **51.3** |
| maximum daily discharge for the year (l/s) | **488** | **568** |
| minimum daily discharge for the year (l/s) | **2** | **2** |
| annual temperature (°C) (Dôme des Petites Rousses) | **-0.5** | **-1.0** |
| annual precipitation (mm) (Alpe d'Huez / Altiport) | **1223** | **1154** |

**Table 2: Some characteristic variables of French glacierized basins. ( Gaudet F., 1973)**

| Station | area .(km²) | %glacier | elevation (mean in m.) | modulus of annual disch. (l/s) | Specific modulus. (l/s/km²) | annual depth (mm) | Période |
|---|---|---|---|---|---|---|---|
| Arveyron MER de GLACE | 77.98 | 51 | 2780 | 5.16 | 66.17 | 2103 | 1950-71 |
| Arve aux FAVRANDS | 205 | 33 | | 13.5 | 66 | 2090 | 1961-68 |
| Tré-la-Tête | 20.9 | 42 | 2890 | 1.53 | 73 | 2303 | 1958-67 |
| Isère à VAL d'ISERE | 43 | 17 | 2695 | 1.82 | 39.6 | 1250 | 1951-70 |
| Arc à BONNEVALl | 81 | 29 | 2754 | 3.61 | 44 | 1400 | 1948-58 |
| Romanche à PLAN l'ALPE | 43 | (16) | | 1.62 | 37.7 | 1190 | 1951-70 |

one month per year, are very irregular.

It is also shown that the year 1992 is warmer than year 1993: the discharges are higher than in 1993.

In conclusion the annual discharge of the glaciary regime shows a constant annual level, and a strong seasonal variation.

*Discharge - mass balance relationships.*

The dependance between mass balance and annual discharge has been examined. The relation between both is the following :

$$PA - QA - EPA = VA$$

where :

PA = annual precipitation on the glacier (mm).

QA = annual discharge in the outlet of the glacier (mm).
EPA = evaporation (mm).
VA = variation in volume (mm)

.

The meteorological values for the glacier area were adjusted depending the elevation . Without other data, simple assumptions were made:

- a rate of -0.65°C per 100 m. of elevation for the temperature.
- a increase of 60 mm per 100 m. of elevation for the precipitation.
- a constant evaporation value: 200 mm for a year (minimal value, the maximal value would be near 400 mm).

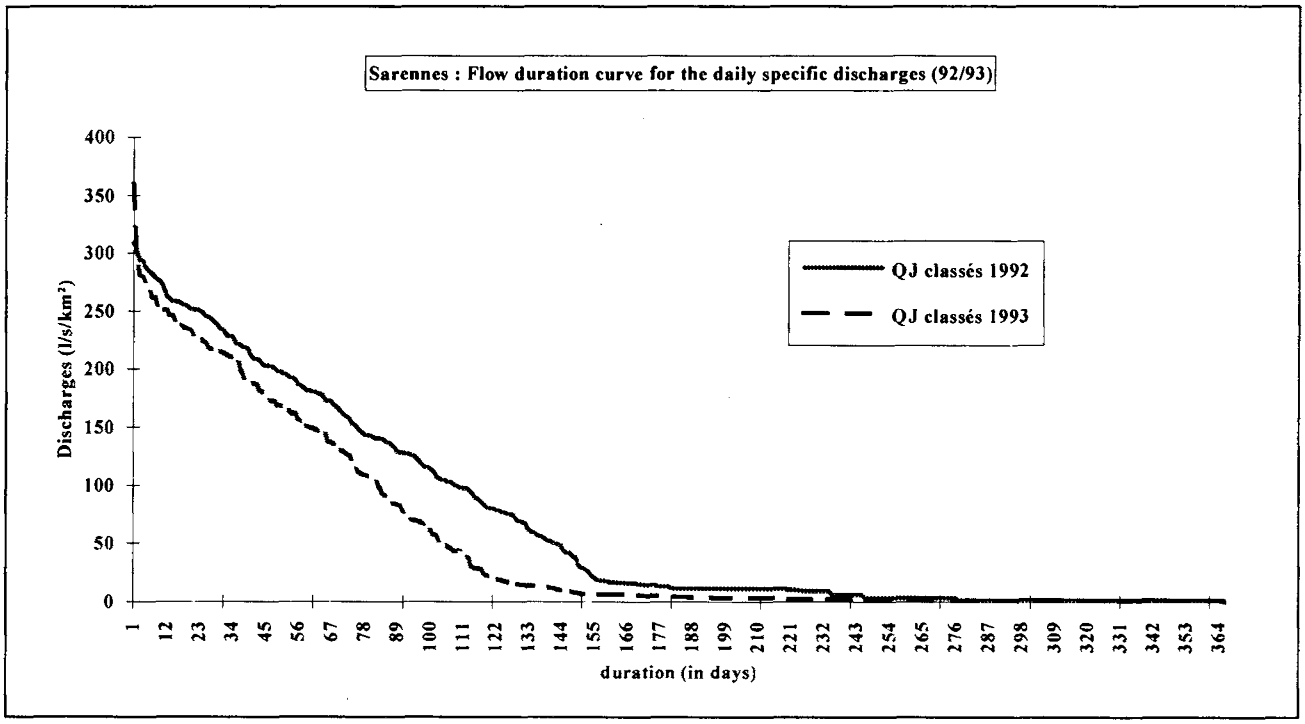



Figure 8. Flow duration curve for the two years 1992 and 1993 (from daily specific discharges)

With these values, a difference between the mass balance and the hydrological balance was found equal to **- 225 mm.** for 1992 and **+ 280 mm.** for 1993 (including the ice thickness lost by the glacier during the icemelt period). These differencies could be explained by :

- an uncertainty about the karstic supply.
- an uncertainty about the precipitations values.
- an uncertainty about the evaporation data.
- and of course, an uncertainty about the measure of water high and the rating curve.

**These differencies between both balances can be accepted, with a relative error comprised between 10% and 15%, which is finally correct. But this hydrological balance contains uncertainties.**

*Seasonal variations.*

The glaciary regime is a regular and simple regime, having a melt period with high discharge in summer (june to september), and a long period of low discharges in winter.

<u>Monthly values of discharges, and relation with precipitation and the temperature.</u>

The monthly values of discharge, precipitation (runoff wave) and temperature are indicated in figure 9 for the year 1992.

This figure shows a strong variation of monthly discharges over the year, the occurrence of the highest discharges do not correspond with that of the precipitation which is the proof of a strong snow retention. Three periods of typical discharge regime can be observed :

- the summer (june to september)
- the intermediate months (april, may, october, november).
- the winter (december, january, february, march).

The curve of the temperature is similar to that of the discharge, showing a real dependance between discharge and temperature for this time step. This parameter is the most important to explain the runoff, because a precipitation event can produce no discharge if the temperature is low. In addition to that, precipitation often decreases temperature, and subsequently decreases the discharge, not as usual regimes.

*Daily fluctuations of summer discharges.*

There are daily fluctuations of the discharges for all the glaciary rivers, due to the daily fluctuations of temperatures *(Obled, 1971 - Power J.M., 1985 - David & al., 1984 - Ferguson R.I., 1985 - Fountain & al., 1985).*

straight, and descending curves rather convex, and all the more because the minima are low when the time gets closer to the evening and temperatue drops, then the melt area decreases also, and the melting decreases twice.

Figure 15 shows observed discharged and calculated discharges for august 1992. The calculated discharges are obtained by a multilinear ascending regression between hourly discharges and hourly temperatures with a 0 to 12 hours lag. The parameters of the regression equation are:

TH4, TH9, TH12 (THi is an hourly temperature with a i

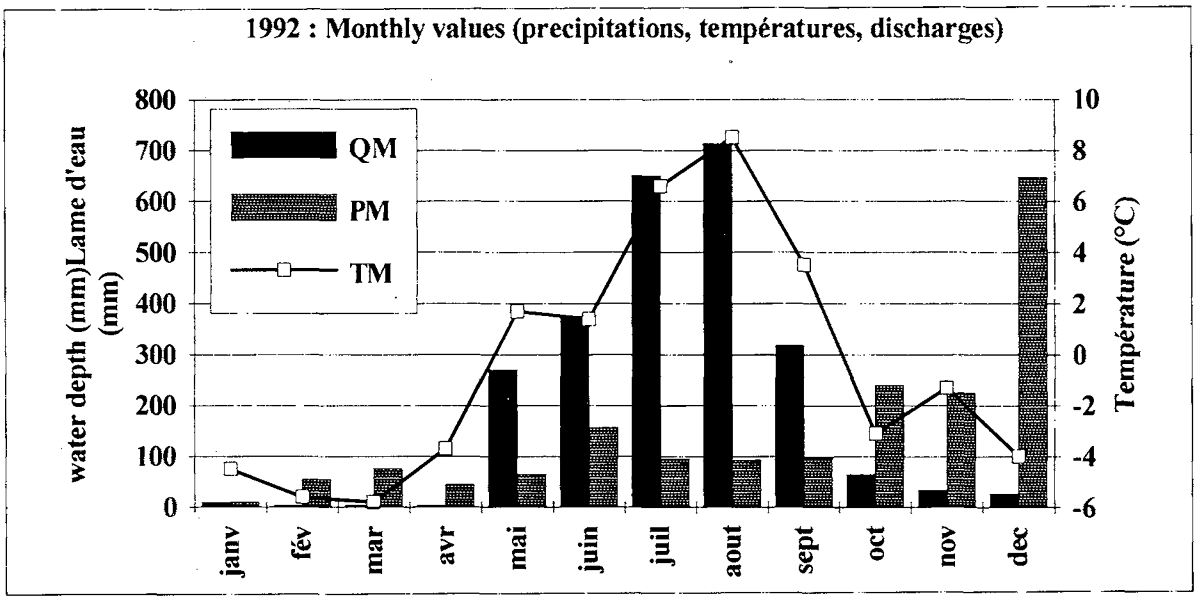



Figure 9. Monthly values of meteorological variables : year 1992.

These variations were studied for several periods during the melt season, from may to october.

Figures 10 to 14 show the influence of the hourly temperature in the form of the daily hydrograph. To sum up the results, it can be concluded that, except precipitation, hourly discharges and hourly temperatures have roughly the same shape. The drawing is more and more regular as we progress in the melt period: in the beginning of the melt season, the seepage of water through the snow cover is more difficult than through the internal circulation system of the glacier ice at the end of the season. Furthermore the ice stronger reacts than snow to the radiation, because the albedo of the snow is higher.

Finally the concave or convex form of the daily hydrograph can be observed. The ascending curves are

hours lag). The equation is in log-log. The TH4 parameter corresponds to the four hours between the peak of the hourly hydrograph and the peak of the hourly thermograph. The other two parameters can perhaps be explained by the asymetric form of the discharge curve. The correlation coefficient is equal to 0.99.

*The discharge-duration curves (with an instantaneous time step) and their interpretation.*

The discharge-duration curves *(Galèa G., 1989)*, with an instantaneous time step, between instantaneous discharge and the continued duration when a threshold discharge is exceeded are indicated in figure 16 for the two years of the study. The graph gives also the number of floods for each threshold discharge.

For the discharge-duration curves, there is a break near the 350-400 l/s., this value corresponds to the threshold of the daily floods of the summer. The other curve (number of floods for each threshold discharge) ve the half of the maximal instantaneous discharge) was made for the two years. Except for some outliers occurred during complex floods, a value around 12 hours is found, corresponding to the daily summer floods.

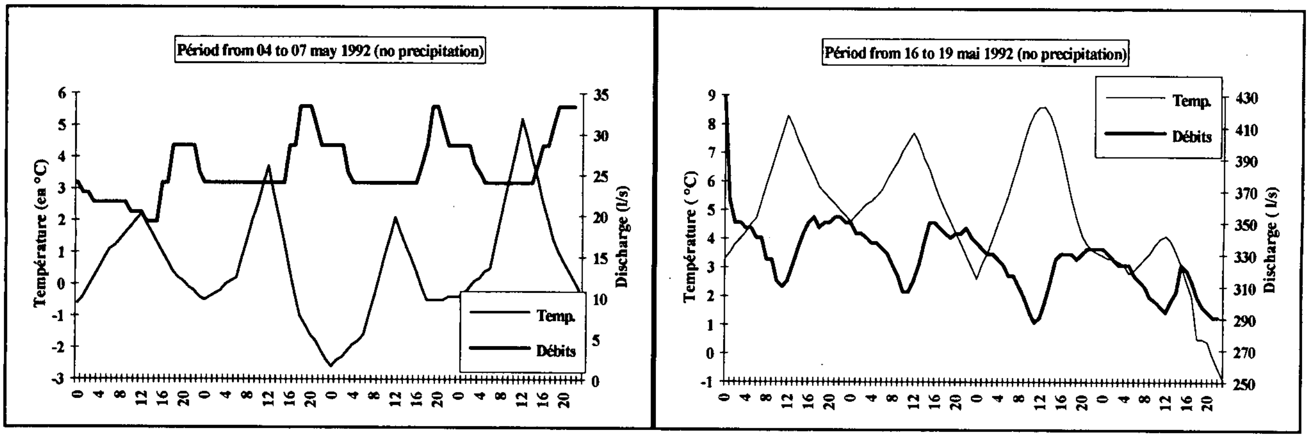



Figure 10 and 11. Link between hourly discharges and hourly temperatures for the periods of may 1992.

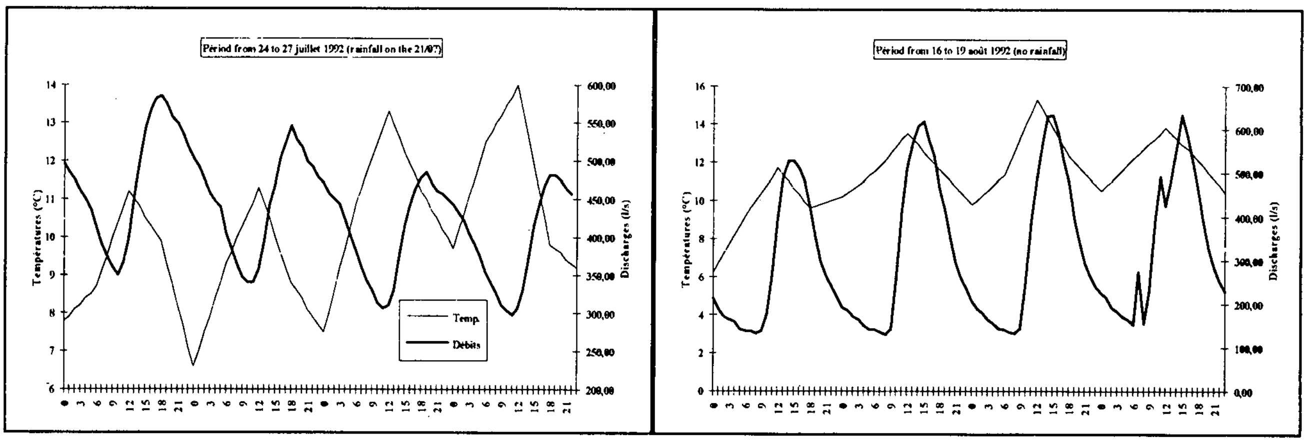



Figure 12 and 13. Link between hourly discharges and hourly temperatures for the periods of july and august 1992.

shows that the maximum corresponds to the same value.This 350 l/s value can be interpreted like the "minimum of the maximum summer discharge".

A very few floods are exceeding 700 l/s : beyond this value, we meet rare floods (storm during icemelt).

For the number of floods by threshold-discharge, there is another small peak near 25 l/s. This value corresponds to the discharges during the autumn or the spring, where the temperature is near zero degree, sometimes under, sometimes above, with the discharges that vary around this 25 l/s value.

The research of the characteristic duration (basin characteristic : it is the duration when the discharge is abo-

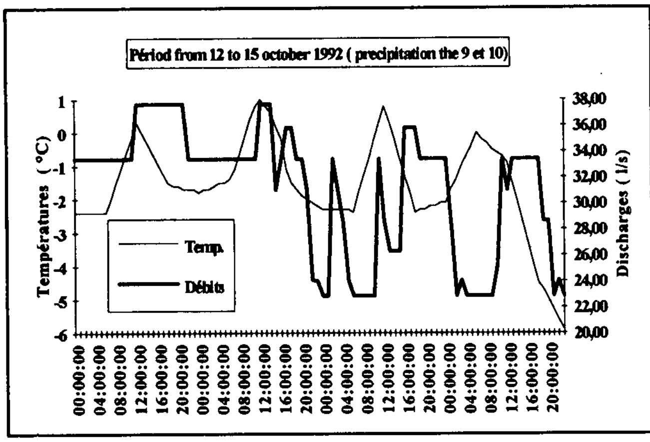
## CORRELATIONS BETWEEN METEOROLOGICAL VARIABLES.

*Correlations between discharge and meteorological variables*

In this study of the Sarennes glacier the method of multiple correlation is used, according to the method applied for the Grande Dixence dam (Lang & al., 1985). The aim was not exactly to find a model, but to observe the simple and partial correlations between the discharges and the meteorological variables (precipitation P, temperature T, and P*T, with a 0 to 5 days lag).

The correlation coefficient are indicated in the figures 17 and 18.

The melt season is divided into three periods : begin



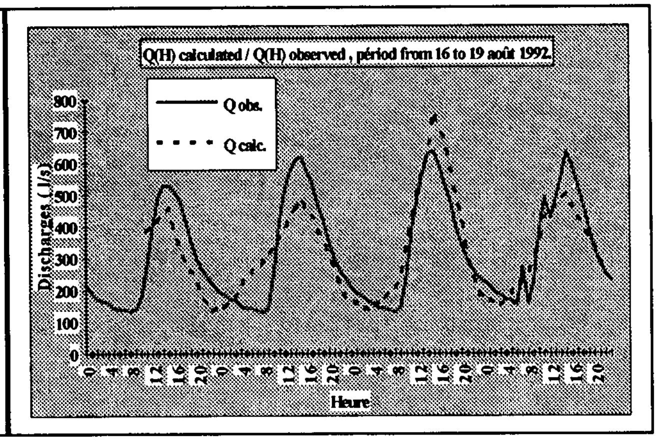




Figure 14. Llink between hourly discharges and hourly temperatures for october 1992.
Figure 15. Observed discharges and calculated discharges with a hourly time step for august 1992

(half may to half july), middle (half july to the end of august), end (september to half october). The two years are grouped together.

The analyse of the results shows for the simple correlation:
- a strong auto correlation for the discharges.
- a strong correlation with the temperature (the best is for T(J-1))
- a low but negative correlation with the precipitations.

The analyse of the partial correlation shows some other results :

- always a strong relation with the temperature.
- the interest to take the P*T variable (good coefficient).
- always the negative influence of the precipitation : when it rains, there are clouds, the total radiation increases, so the melt.

For the "begin" and "end" periods, there are high multiple correlation coefficients (0.80), but worse for the "middle" period probably because of the changing melt from july to august : the icemelt appears after the snowmelt, with a lot of differencies between the two runoffs.

## CONCLUSION

*Conclusion on measurement.*

Measurements in the high mountain are difficult (elevation, strong slopes, snow, no access..). But after these problems have been solved, the results are interesting: Glaciary regimes are not often studied for a long period. For the future, the rating curve must be improved with new dilution gaugings, and new probes have to be installed that accept higher water level.

For the representativity of the meteorological variables a new meteorological station on the glacier must solve this important problem.

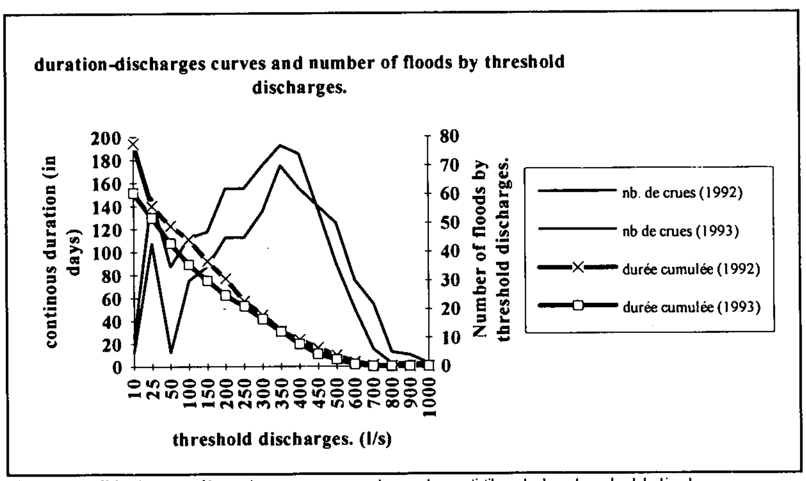



Figure 16. Discharges-Durations curves and number of floods by threshold discharges.

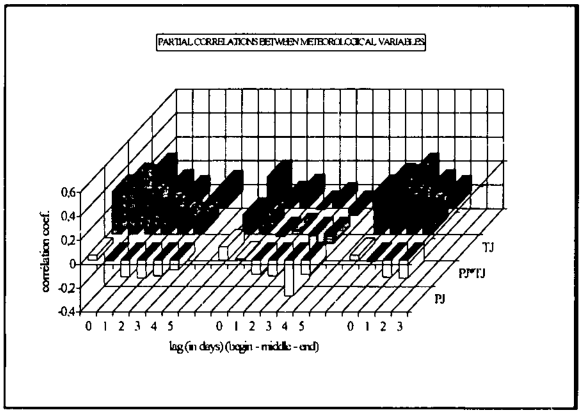



Figure 17. simple correlation coefficient between QJ and meteorological variables (QJ, P, T, P*T, lag 0 to 5 days)

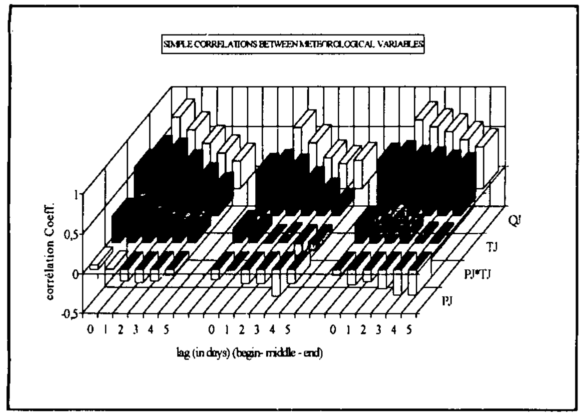



Figure 18. partial correlation between QJ and each separate variable (P, T, P*T, lag 0 to 5 days).

A new gauging station on the same river but more downstream in the valley will help to describe the scale effect and to study the difference between the glaciary regime and the snow-glaciary regime.

Conclusion on typology.

The described typology shows a normal glaciary regime(Parde M., 1933), with the maximum discharge in august or july, depending on the year. The annual runoff/mass balance relation leads to a different runoff total of about 10 to 15%, which can be accepted when the uncertainties of the measures are being taken into account..

The description with different time steps (annual, monthly, daily, hourly) allows to precise the values of annual specific discharge, the form of the monthly hydrographs, in relation with those of the monthly precipitation and the monthly temperature. The relation with temperature appears to be strong as it is a glaciary regime characteristic. The daily fluctuations of summer discharges were analyzed depending on the three melt periods, each period presenting a characteristic form that depends on the runoff conditions for that period. A calculation with an explanatory model has been done on the icemelt period where the daily fluctuations are the more regular, with a multilinear regression between hourly discharges and hourly temperatures, with a 0 to 12 hours lag. Then the discharges-duration curves were established to find again the summer floods (around 400 l/s) and the floods concerning the intermediate months, when the temperature appoaches the zero degree. With the next data sets of discharges, we would be able to find the discharge-duration-frequency curves (Q-d-F model, *Galea G. 1989*).

Concerning the explanatory variables and the modeling of the daily precipitation and the hourly temperature, good results were foundfor the period of "beginning " and "end" (correlation coefficient equal to 0.8), but less good for the "middle" period, which is more heterogenous (passage from snowmelt to icemelt). We observe with these partial correlations that the relation is strong between discharge and temperature, good with discharge and the product temperature with precipitation, low and negative with the precipitation.

The continuation of collecting instantaneous water level data on the two gauging stations, and data from the new meteorological station must permit to improve these different points.

The first data sets are encouraging to continue the study and to apply different models, to study floods, to find other explicative variables (radiation)... The future research in this E.R.B. will be interesting for the study of the climatic change.

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