40 YEARS SNOW COVER MEASUREMENTS IN FRANCE :

Network evaluation, forecast interest

(Application of historical and realtime data to the multipurpose of water management)

by

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ABSTRACT

For nearly 40 years, EDF (French National Electricity Board) has been using a snow survey network in order to forecast snowmelt inflow for the purpose of water management (hydropower optimization, agriculture, water-sports...) during the end of winter, spring and summer. This network, set up at altitudes between 800 m and 2700 m consists of 240 manual gauging sites (having dropped from 650 in the late 60's), in Alps - Pyrénées - Central range mountains.

Meanwhile, in order to get realtime data, EDF has developed an original automatic level gauge service : the "TELENIVOMETER". This equipment can measure, once a day or more , the density of different layers of snow (10 cm slices) the snowdepth and the air temperature and thus deduces the water equivalent. The data can be collected by satellite (ARGOS) or by telephone for lower-altitude sites.

20 years snow cover measurements in France : Network evaluation, forecast interest (Application of historical and realtime data for water management)

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INTRODUCTION

EDF (French Electricity National Board) is a nationalized corporation producing more than 400 billion kWh of electricity for domestic and industrial use and for sale to European companies. It is one of the leading companies in France and even world wilde in the field of electricity judging by its turnover and size.

Within EDF, the production and transport directorate has the responsibility for managing a park of nuclear, flame powered thermal, and hydraulic power stations (100 GW installed power) and the high tension transport network. The energy stored as water in reservoirs represents 10 billion kWh produced by stations situated at the foot of the dams, to which must be added 10 billion kWh produced downstream by stations on the rivers down towards the sea.

Given this development, the water resources service of the General Engineering Division (DTG) has progressively set up, over 40 years, a network for measurement of the snow cover on the major French mountains chains, which is used for the calculation of the long range water supply forecast.

The data collected by this network is mainly used to establish the forecast of snow melt inflow for hydroelectric power, progressively taking into account, both economically and physically, the water requirements for agriculture and water sports, as far as planning and management are concerned.

Together with other hydroclimatological information, both recent and past, (rainfall, temperatures, water discharges, water table levels, ...) the measurement of the water equivalent of stored snow is highly economically valuable information used to help make decisions in the optimum management of the water to be retained in the dams.

These decisions must respond to the whole range of applications of the installations which are often antagonistic (power, agriculture, tourism, drinking water, flood and accidental pollution protection...) especially in climatological periods when water is scarce.

1 - THE YEARS 1946-1965 : A VERY DENSE NETWORK OF MANUAL MEASUREMENTS, BUT A DELICATE OPERATION

1.1 - The source : the need to make the best use of hydropower

Just after the war, the rebuilding program made it necessary to call on all the national sources of electrical power production. The low level of fossil fuel resources naturally available led to the immediate implementation of readily available hydro-electric power. In this respect, France had the double advantage of a high level of rainfall - 825 mm annually which makes it the second wettest country in Europe after Italy - and a high relief : 10% of the country is at an altitude of more than 1000 m and 2% more than 2000 [fig 1].

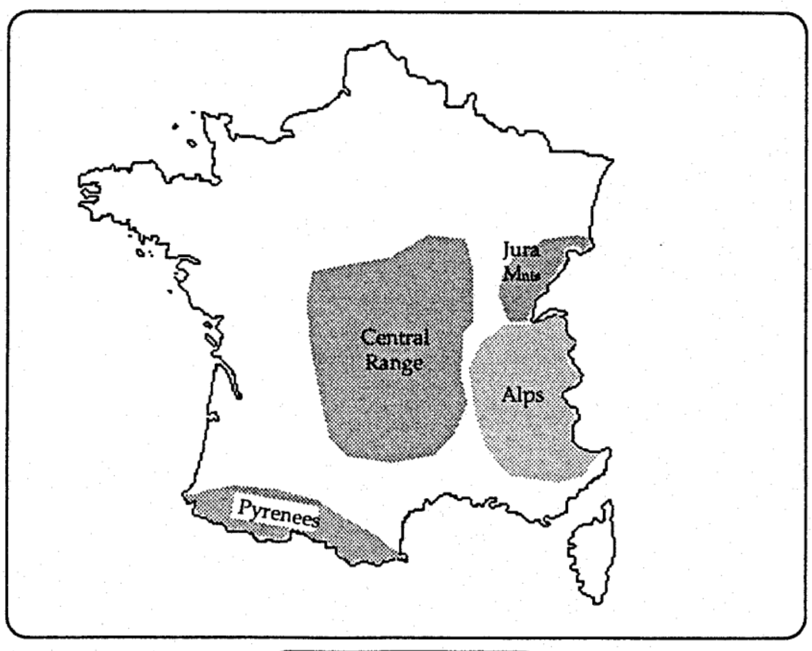


Fig 1
France and its mountains

The annual reserves of surface water in France is on average 150 billion m^3, of which the snow cover in the medium and high mountains contributes to a non-negligible part of the renewal of the stock, with a variability of ± 30%.

The global water equivalent of the snow cover, which comes from the spring and summer thaw, alone represents in effect nearly 10 billion m^3 for an average year, with a ratio of 1 to 4, between highly deficient years (5 billion m^3) and highly excessive years (15 to 20 billion m^3).

EDF are able to stock 7 billion m^3 in its reservoirs, situated essentially in the Alps, the Pyrenees and the Central Ranges. Most of this water comes from snow melt during the spring and the summer, in the high and medium mountain ranges. Hence EDF's strong interest in the dynamic economic management of these reservoirs, aimed at obtaining information on and following continously the evolution of the snow cover by measuring not only the depth of snow, but more importantly its density and thus its water equivalent.

This is why, in parallel with the construction of large hydro-electric reservoirs in the 1950's, an extensive network of snow measurement sites was installed.

This network is remarkable for two reasons :

- first of all, it was, historically, the first network of snow level measurement in France, and even up to the present day, the only one of its size. The few stations existing before the war were due to local intiative (forestry, local electrical companies) and used without any systematic or standardized procedure
- secondly, this network has a very high density of measuring points (up to 650, covering 10% of the country making it one of the richest networks in Europe (including Switzerland).

1.2 - The means : the installation of a (network) manual measurement

This network consisted of manual measurements (repeated 5 times) of the thicknose and average density of the snow mantle, in typical controlled situations. They were carried out each week for inhabited areas, at the beginning of each month for higher altitudes and at the beginning of the month of April for the more inaccessible sites.

The sampling sites, identified by a metal rod 4 to 6 metres high concreted into the ground, were the subject of a rigorous selection procedure. Sites which proved to be unrepresentative (exposed to the wind) or dangerous or even impossible to reach some winters were abandonned after several years of measurement.

After an in depth analysis of most results and a systematic study of their correlation with the melted snow contribution to the river discharges, the present network (1992) is now made up of 240 selected sites, at altitudes between 800 and 2700 m.

The observers, mountain farmers, ski monitors or hydropower plant workers use dismountable aluminium sampling tubes which can be carried in back-packs.

The sampling tube is forced vertically into the snow layer down to the ground, and is then pulled out with its complete core of snow. Weighing the full sampling tube enables the weight of the snow core to be calculated by subtracting the weight of the empty tube.

A complete measurement is made up of 5 samples taken around the identification rod. To date more than 80 000 surveys have been carried out.

The sampling tube used is the "EDF 54" model. This has a blade of 54 mm in diameter, 10 mm of water corresponds to 22,9 g.

The tube is weighed using a spring balance with 20 g graduations. The precision on the water equivalent is therefore of the order of 10 mm.

The "EDF 54" sampler is heavier and less easy to use than the "North American" MONT ROSE",model, invented by the forestry officer CHURCH in 1909 (37,7 mm in diameter, 1 ounce corresponding to 1 inch of water).

Apart from of recruitment (the difficulties) related to sociological evolution, manual sampling of the snow cover can only be carried out using long and sometimes dangerous rounds. Also, during winter, one cannot be certain to carry out the sounds at useful and optimal dates.

2 - AUTOMATIC MEASUREMENTS : DEVELOPMENT OF ORIGINAL AUTOMATIONS ON EDF'S OWN INITIATIVE

The need to obtain information as soon as possible before the end of the winter season, so as to be able to use the water in the reservoirs during the current winter, when the power has its highest value, while guaranteeing the refilling for the new winter, as well as preserving the safety of the personnel for the poorly accessible sites, explains the effort that the DTG has made since 1965 towards the automatisation of the measurements and the transmission of the data.

Two types of remote level gauges have been developed : these are automatic devices which remotely measure the water equivalent, the thickness and the density of the snow layer.

2.1 - The first "prehistorical tests" : totalizing devices

The first tests to automate measurement go back to the beginning of the century with the development of the MOUGIN level gauge. This consisted of a cylindrical tank with a cross section of 20 dm^2, and an opening of 2 dm^2, placed on a support 6 m from the ground and protected from the wind by a collar.

The tank was emptied once a year before the winter.

The contents were weighed and the antifreeze, a solution of 50% calcium chloride renewed and covered with a litre of oil to prevent evaporation.

During the winter, using a ruler the level of the tank was read off to the nearest mm to determine the precipitation.

A network of 150 measurement points was progressively set up between 1947 and 1960.

In spite of the precautions taken, the results were very disappinting.

Many of the gauges were put in unrealistic situations, exposed to too much wind, which gave rise to readings clearly too low.

Measurements clearly too high were also obtained due to snow or frost sticking to the mouth or collar and creating a wider effective mouth.

Finally, the unreliable and imprecise devices were progressively abandoned at the beginning of the 70s.

2.2 - The remote level gauge : remote measurement of the height, water equivalent and density of snow.

The principle of this device is to measure the attenuation of a beam of radiation passing through the snow layer.

The radiation is supplied by a weak radioactive source (of several tens of mCi) and is measured by a Geiger counter. The dosage received by the latter is exponentially reduced by the thickness of water through which the radiation passes and is independent of the physical state of the water : snow (dry or wet) with layers of ice.

2.2.1 - The early developments

The measurement of the water equivalent of the snow layer by the attenuation of radiation has been the subject of experimentation in many countries since 1950.

The publiccations and information obtained since then show that the effort was generally limited to tests of a small number of prototypes, but was not followed through up to a regular and satisfactory usage over several years using devices manufactured in series.

In France, 10 devices, with on site recording but without remote transmission were installed in 1952 in the Durance bassin. They never provided usable observations. This attempt was premature given the technological competence of the period. In particular the measurement of the quantity of electricity released by the Geiger counter by integration into a condenser rapidly turned out to be imprecise.

In 1959, two networks were installed in the west of the USA for the US Corps of engineers.

In 1961, the administration decided to have a study of the validity of the devices undertaken by the university of Moscow (IDAHO).

The difficulties encountered were largely due to the type of detector chosen. The low activity of the source had lead to the choice of a scintillation detector using a photomultiplier tube.

More sensitive than Geiger counter, it turned out to be more complex and especially subject to drift.

EDF nevertheless continued in this direction and in 1963 installed 2 devices in the Grenoble region at 1350 m and 2540 m.

Designed for remote measurements by radio of a snow level up to 4 m and a water equivalent of 1200 m, the first results were very encouraging.

Many technological evolutions enabled a range of perfectly stable devices to be developed by 1975.

2.2.2 - The EDF-DTG beam remote level gauge

Two types of device are in service at present. They are both autonomous in their power needs which are supplied by batteries recharged by a solar panel.

The vertical beam remote level gauge provides a direct measurement of the water equivalent of the snow layer using an ultrasonic measurement. This device which is used in mid range mountains between 900 and 1500 m and for a snow layer which does not exceed 2 metres, does not influence the snow mantle.

The water equivalent and snow height are measured every 4 hours. An hourly check of the air temperature enables a precise surveillance of the 0°C isotherm at these medium altitudes, where melting phenomena can set up very rapidly.

The transmission of the information can be made at any time due to an automatic telephone system. For very isolated sites, a version using transmission by the Argos satellite has been successfully tested.

Ten devices of this type are in service at present, mainly in the Central Ranges and theJura mountains.

The horizontal beam remote level gauge measures the thickness and density of the snow mantle in 10 centimeter layers and thus deduces the water equivalent.

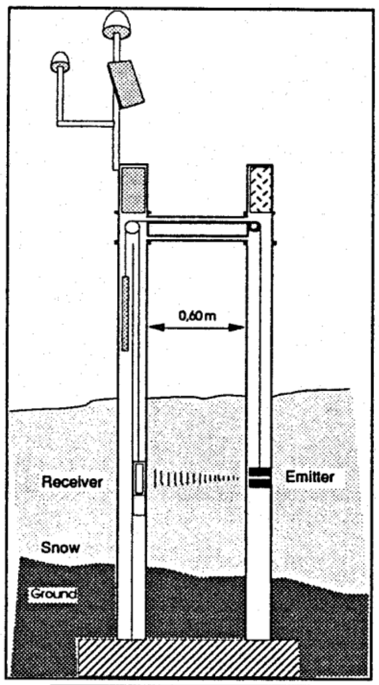


Fig 2 : Telenivometer
Horizontal type

It requires only a very weak radioactive source (10 mCi) which only comes out of the snow for a few seconds per day to about 10 cm. It has no upper limit for the snow height except that of the height of supporting posts (6 metres).

The measurement is controlled each day at a fixed time by a clock.

The transmission of the data is carried out entirely via the Argos satellite using a transmitter. The measurements are then sent to Grenoble from the CNES at Toulouse by a rapid computer telephone line.

Each winter, more than 200 remote measurements are collected, some of which are completed by air temperature measurements.

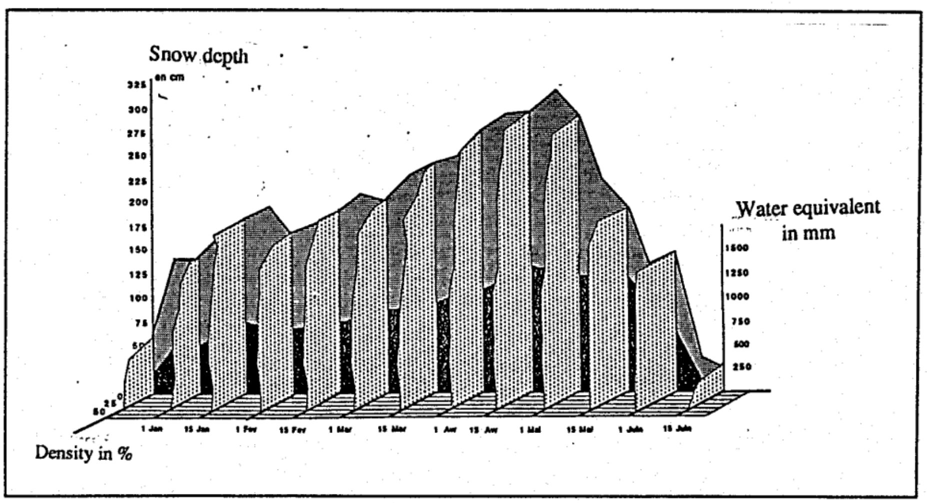


Fig 3 - Agnelin telenivometer
Snow depth/density per slice for 1986-1987

30 sample sites are currently equipped with this device in the Alps and the Pyrenees.

A horizontal beam remote level gauge has also been installed in the Principality of Andorra in 1991, as a demonstration for the Spanish minister of public works and the Ebre Agency. The Swiss electrical company Grande Dixence SA has ordered two such devices for installation in the autumn of 1992 in the high Rhône Basin.

2.2.3 - The EDF snow survey network in 1992

About 40 sites in the French mountains have been remotely monitored over the last 15 years (20 years for some sites).

Over more than 10 years, development has continued, with the adoption a of total quality approach. Tests on all the electronic and mechanical components according to standardized procedures have enabled remarkable reliability to be reached. The number of breakdowns over the whole park is less than 1 per year.

The robustness of the equipment has been largely demonstrated in the hostile environment found in high mountains. After 15 years of operational use, only one device has been lost. Damaged by the blast of an avalanche, it nevertheless continued to deliver usable information for the rest of the winter.

All the same, while the reliability of the remote measurements is excellent, it is essential to maintain a complementary network of manual measurements carried out by mountain people who have largely contributed to the capital of information about the snow.

The conscience of the observer, devotion and courage are appreciated, without whose continuing action, it would not have been possible to judicously install these 40 automatic devices which represent a large investment for EDF.

2.3 - Perspectives : complementary information coming from satellite imaging, should in the long term provide better information on end-of-melting phenomena.

Whereas the evaluation of the snow stocks on high mountains (> 1800 m) by teledetection from the analysis of satellite photos appears to provide little information during the period when the snow is accumulating (up to mid April on average), as soon as the thaw is largely underway, and more precisely from mid June to the end of July, the evaluation of the surfaces still covered with snow takes on a new interest and isolated measurements lose their spacial representivity.

The managment of hydroelectric reservoirs at the end of the refilling stage could therefore be refined.

Whereas we now have high definition satellite images (Landsat, Spot) and quite refined landscape models, the operational evaluation of the satellite data calls for a regular availability (weekly) of satellite photos for a two month period which, in practice, cannot be achieved due to cloud cover.

One must then be able to associate the evaluation of the snow covered surfaces to the ground measurements in order to calculate an estimation of the snow stocks spread over the mountain chain.

This must be carried through for several years in order to build up a data file for correlation studies with the early summer additions to the water flow, the left over of the thaw.

It may soon be possible to improve these estimations using airborne radar which provide profiles of the thickness of snow mantle.

The financial and technical barriers are still high, but a feasibility study is currently being carried out.

3 - DATA BANKS - APPLICATIONS

The results of historical measurements have been used to build up a living data base of the height and water equivalent of the snow mantle. This is currently growing with observations coming both from manual measurements and from daily continuous remote measurements of the snow mantle to enable an optimisation in the long and short term of the management of the reservoirs with respect to the potential snow run off.

3.1 - Structure of the data bank

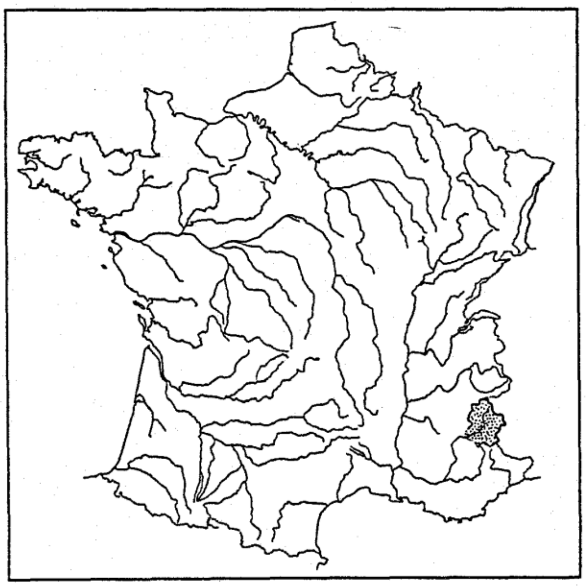
Apart from observations taken each year (one or sometimes more) during the period 1950-1975, on about 50 sites by observers, we have available at present, readings of the snow levels - water equivalent of the snow mantle in the Alps, Pyrénées and Central Ranges as follows :

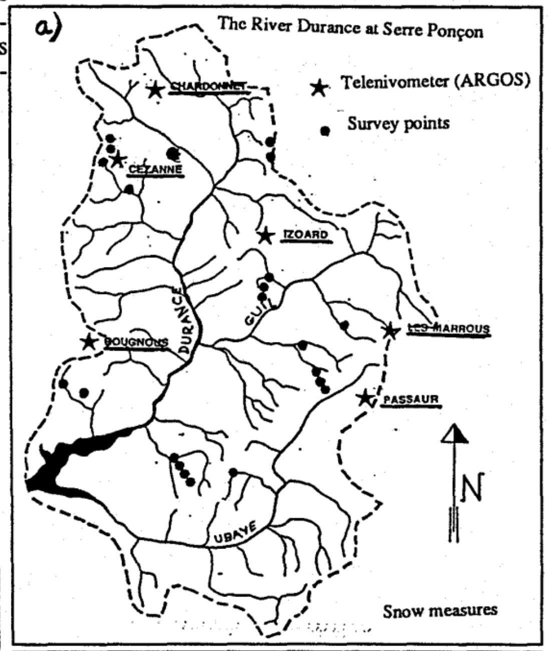
- for sites equipped with remote level gauges, daily observation (October to June) for about 15 years,
- for about 50 sites, observations carried out on the 1 January, 1 February, 1 March, 1 April, and 1 May for more than 35 years,
- for about 20 sites, weekly observations for 40 years,
- for about 150 sites, observations taken the 1 April over the last 35 years.

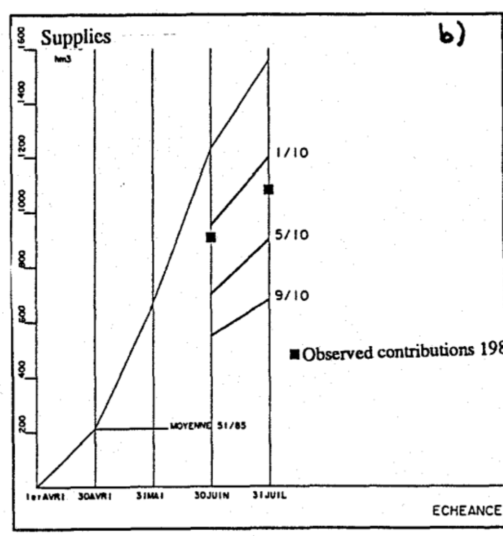
Study of the chronological profiles of the water equivalent of the snow mantle, shows the interannual variability (there is a 1 to 4 ratio between the lowest and highest snow level on a site) but also a spacial variability of the snow level during a year, although there are good correlations between certain zones. At a given altitude the snow stock is very variable depending on the region. The temporal variability of the constitution of the snow mantle in a given place is very high. We have demonstrated the importance of the history of the snow layer during the winter on the modulation of the snow thaw wave in spring/summer during fine studies of forecast melt run off : the water efficiency of the snow mantle.

3.2 - Calculation of forecast melt inflows

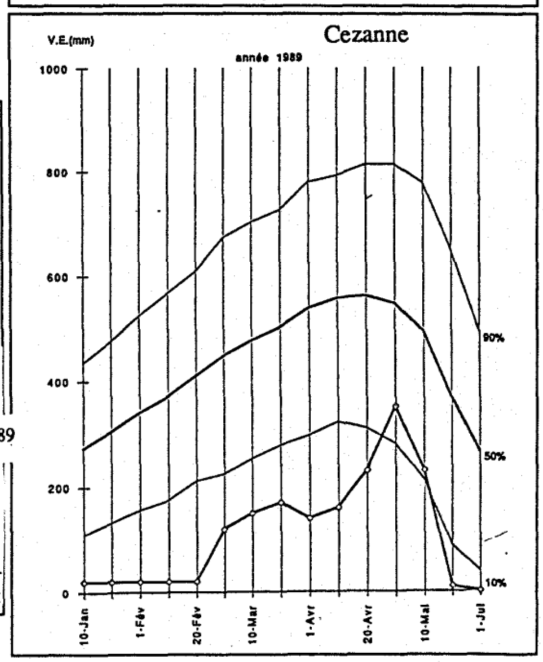
The numerical forecast of inflows due mainly to long term snow melting can only be realized because there is a delay of two to three months between the maximum build up of the snow mantle and the point of the thaw wave. For the Durance River (fig 4a), the snow survey netwok (4b), with for instance the results collected at the telenivometer of Cezanne (quite in deficit) allows nevertheless a successfull forecast (fig 4d) for the water supply in Serre-Ponçon







Graph showing the global contributions at the end of each month having 1,5 to 9 chances in 10 of being exceeded



Only rarely, in countries such as the USA, these forecasts are established from linear models tied by multiple correlations between on the one hand, the melt inflows and on the other hand, winter rainfall measured at medium altitude, the state of underground reservoirs, the snow cover, and the temperature. These are calculated from the 1st January of each year, with an update at the begining of each month or each fortnight up to the 1st June for the summer inflows in about forty catchment basins.

The meteorological events of the summer which cannot be forecast at these dates are treated as random inputs for which the mean values and the standard deviation are known. However, the daily follow-up in real time of the water content of the snow mantle can sometimes be used to modify the forecast management of the reservoirs in the case of a large variation, without waiting for the full calculation of the forecast.

In general, the forecast calculation can be used to reduce by 40 to 50% the typical free variation of the summer inflows.

The table shows two examples of inflows.

ISERE AT PIZANCON (11320 km²)		
	Annual inflows	May-August snow melt inflows
Minimum (1949)	5,5 billion m^3	2,5 billion m^3
Average	10,5 billion m^3	5 billion m^3
Maximum	14,5 billion m^3	7,5 billion m^3
DURANCE AT CADARACHE (11700 km²)		
	Annual inflows	April-July snow melt inflows
Minimum (1990)	3 billion m^3	1,3 billion m^3
Average	5,6 billion m^3	2,6 billion m^3
Maximum (1977)	10 billion m^3	4,5 billion m^3

3.3 - Fields of application of snow measurements and forecasts

The economical advantage provided by forecasts of inflow due to snow melt does not require demonstrating. It amounts to tens of millions of francs and largely exceeds the investment costs in equipement, software, maintenance and project studies.

We have previously quoted the improvement in the management of the electrical power production facilities in France : in fact, during the winter and in early spring of this year, large accumulations of snow were able to be used to generate kWh of hydraulic power at a low price, by using water stored in the reservoirs without breaking into the potential power of next winter, given the potential of frozen water stored in the mountains which would refil the reservoirs at the next thaw. On the other hand, (we could only use the water in these same reservoirs with caution), if the snow stocks seemed to be deficient. Finally, these forecasts can be used to determine the level of combustibles purchased abroad (coal and oil) in summer for the next winter.

As far as other uses of the water are concerned, the forecasts are valued more by the constraints that will occur next summer :

- attribution of water to farmers for summer irrigation of agriculture,
- targets for dam water levels to enable water sports (races, sailing, swimming) to be held in summer,
- the possibility of preventing floods due to rain and snow melt (especially at medium altitudes),

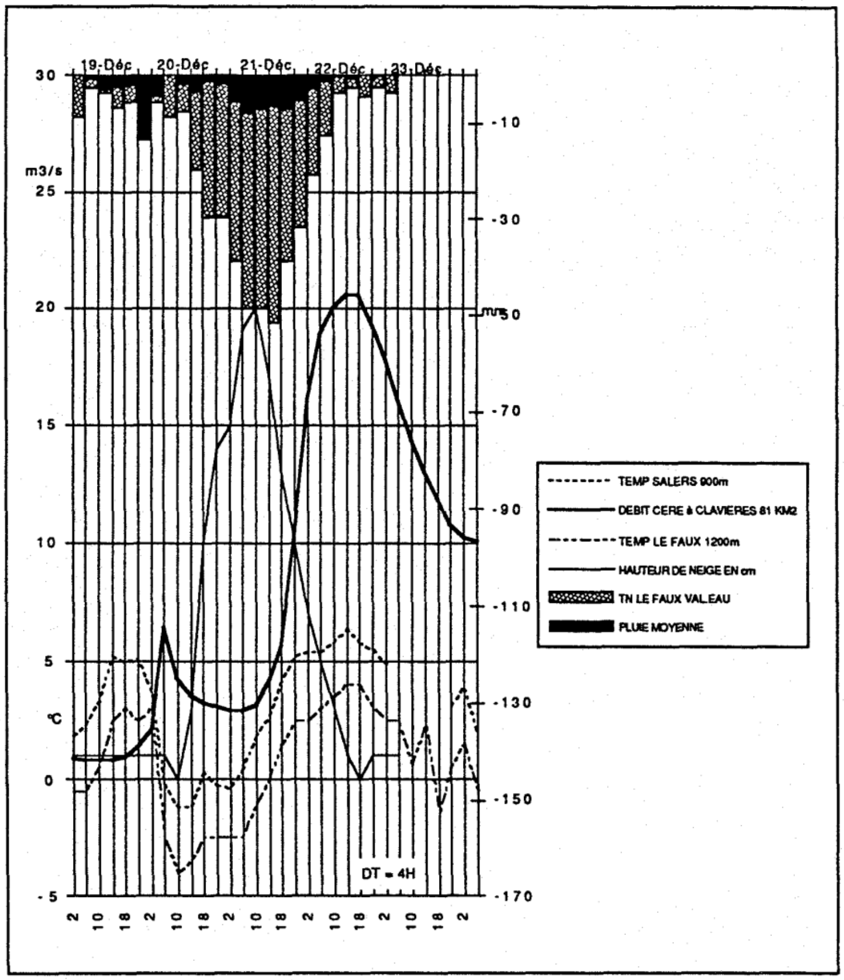


Fig 5 - Flood of the river Cere
December 1991, 22nd - 23th

- the possibility of filling smaller reservoirs with town drinking water for the summer and following winter,
- these contraints, due to the multiple use of the water, become especially important during periods of low water or drought.

CONCLUSION

Based on an original device, the telenivometer, an integrated network of remote monitoring of the snow depth, water equivalent and density of the snow has been built.

Initially designed simply to optimize the electrical power production of Electricité de France, the growing importance given to the mountain requirements for multiple uses of water and the management of water resources, provides the monitoring network and the remote level gauge in particular with a renewed interest.

In fact, this device gives full information likely to interest various users.

We can cite, for example, the techniciens responsible for clearing snow and triggering avalanches, forestry workers, winter sports industries, farmers, water distribution companies, tourist organisations and, of course, hydrologists.

The succession of profiles as a function of time can be used to follow the settling of the various snow layers which can last for many months and which supply important information about the transformation of the snow mantle, the risk of avalanches and the rate of inflow from the snow stock.

The dynamics of the mountain slopes depend strongly on the water content of the soil. For this reason, two devices were installed in 1991 for the Ministère de l'équipement (Ministry of Works) in order to monitor the movement of two landslide sites in the Alps.

Finally, the data collected daily are made available to the general public on a telematic server, minitel screen on the automatic telephone network. This provides the public with the latest evolution of the snow conditions, quality of the surface layers of snow, snow level compared to the average over the last 30 years, giving those interested some indications on the state of the ski slopes.

The strength of demand of the remote level gauges, in France and abroad, is such that EDF is currently searching for an industrial partner for the commercial development of this device.

REFERENCES

S. FERRY : "Methods of snow estimation for mountains catchment areas and their usage for predicticting spring and summer run-offs" - U.I.P.D.E.E - BRUXELLES's Conference - Sept 1949.

S. FERRY and F. LUGIEZ : "Run-off predictions during the thawing of snow reserves" - U.G.G.I - A.I.S.H General Assembly of BRUSELLS 1951 (Volume III).

R. GRARD : Selection of snow measurement sites for the prediction of run-off into reservoirs" - 8^{th} Congress of Alpine Meteorology - VILLACH 1964.

M. VUILLOT and P. GUILLOT : "The horizontal mobile beam telenovometer" - Bulletin A.I.S.H XIII,4 - 12/1968.

D. MARBOUTY, C. OBLED, P. GUILLOT : "Satelite images and snow layer measurement" - La Houille Blanche n° 7/8 1978.

V. DENEAU, C. LEPRIEUR, G. SAINT : "Teledetection of surface snow on the Central Range plateau" ; S.H.F - [Glaciologie section] 12-13 March 1981.

D. DUBAND, J. PINTE : "Choosing representative snow sites in the Northen Alps" ; S.H.F - Section de Glaciologie - 12/13 March 1981 GRENOBLE

P. GUILLOT : "Measurement of the snow layer water equivalent" S.H.F - Glaciology Section ; 4-5 March 1982 PARIS

J. MARTINEZ : "Runoff Modeling from Snow covered Area - I.E.E.E Transactions on Geoscience and Remote Sensivy, Vol GE 20, N° 3 July 1982