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Integration of Field Data into Operational Snowmelt-Runoff Models

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Conceptual runoff models have become standard tools for operational hydrological forecasting in Scandinavia. These models are normally based on observations from the national climatological networks, but in mountainous areas the stations are few and sometimes not representative. Due to the great economic importance of good hydrological forecasts for the hydro-power industry attempts have been made to improve the model simulations by support from field observations of the snowpack. The snowpack has been mapped by several methods; airborne gamma-spectrometry, airborne georadars, satellites and by conventional snow courses. The studies cover more than ten years of work in Sweden. The conclusion is that field observations of the snow cover have a potential for improvement of the forecasts of inflow to the reservoirs in the mountainous part of the country, where the climatological data coverages is poor. This is pronounced during years with unusual snow distribution. The potential for model improvement is smaller in the climatologically more homogeneous forested lowlands, where the climatological network is denser. The costs of introduction of airborne observations into the modelling procedure are high and can only be justified in areas of great hydropower potential.

Introduction

Half of the Swedish electric power demand is covered by the hydroelectric power system. Therefore, good hydrological forecasts during the spring flood period are important. In Sweden one important forecasting tool is a semi-distributed conceptual runoff model, the HBV model (Bergström 1972; Bergström and Forsman

1973; Bergström 1992). Input data are daily values of precipitation and air temperature. The areal precipitation is calculated by weighting point measurements from several stations and is increased with respect to basin altitude. The melt routine of the model is essentially a degree-day approach. In mountainous areas there is a problem with the lack of representative climatological stations and measurement's errors, especially due to aerodynamic losses in winter. Above the timber line the redistribution of snow on the ground causes great variations.

During the last 15 years new ways of determining areal snow pack over large areas have been tested by the Swedish Meteorological and Hydrological Institute (SMHI) with financial support from the Swedish Association of River Regulation Enterprises (VASO). These are:

- Mapping the areal snow water equivalent by low flying airplanes carrying a gamma-spectrometer.
- Mapping the snow pack from a vessel or from a helicopter carrying georadar equipment.
- Snow cover mapping by different types of satellites.
- Evaluating conventional snow-courses.

Attempts have been made to integrate the different methods into our forecasting operations mostly by updating of the snow pack in the hydrological model.

The Gamma Radiation Technique

The experiment with airborne terrestrial gamma radiation technique was carried out in the Kultsjön basin (area 1,109 km^2) during 1980-84 (Bergström and Brandt 1985). The intensity of gamma emission over selected lines was measured during the first autumn (1979) and then every spring before melting. The snow water equivalent can be determined from the ratio between emission from bare ground and from snowcovered ground (WMO 1979; Dmitriev *et al.* 1971; Glynn *et al.* 1985; Kuittinen 1988; Offenbacher and Colbeck 1991). The instrument, a detector crystal having a volume of 16.8 litrs and a spectrometer with 256 primary channels, was installed in a twin-engines aircraft. The flight altitude varied between 30 and 50 m. The energy band 250-3000 keV was used and a short integration length – 200 m – was chosen due to the nonlinearity of the attenuation function.

The project started with 16 lines (263 km) but these were successively reduced to 7 lines (125 km), Fig. 1. In Fig. 2 an example of output from three lines is shown and it illustrates that the snow pack increases with the altitude below the timber line. Above the timber line snow accumulation is very irregular due to redistribution by the wind.

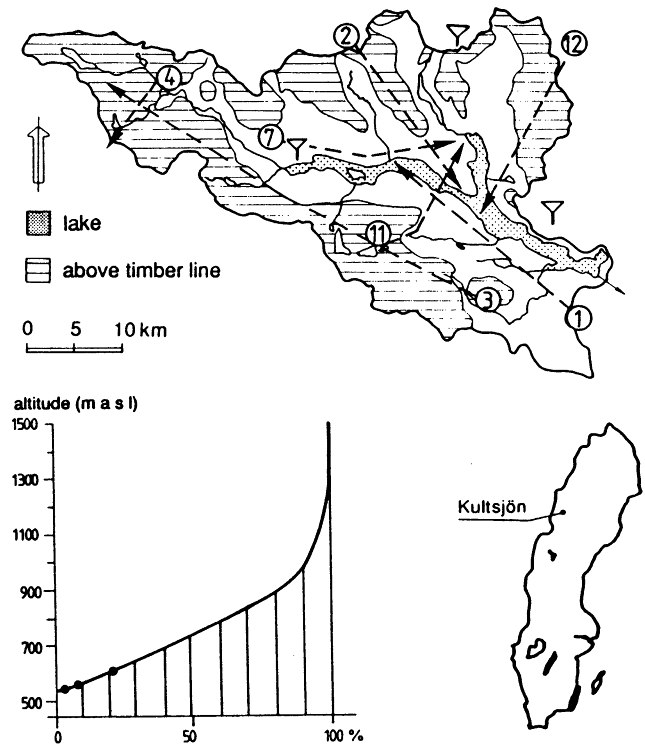

Fig. 1. Location, topography and flight lines over the Kultsjön basin. Area-elevation curve with marked altitudes for the three precipitation stations.

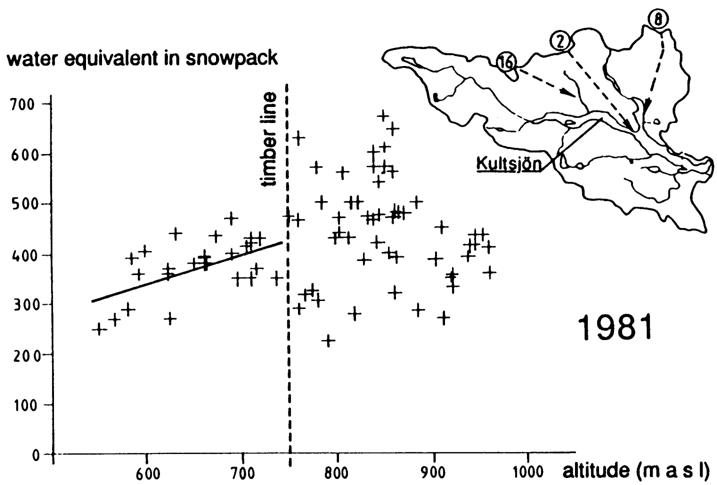

Fig. 2. Relationship between snow water equivalent and altitude along three lines in the Kultsjön basin. The measurements are made by the gamma radiation technique.

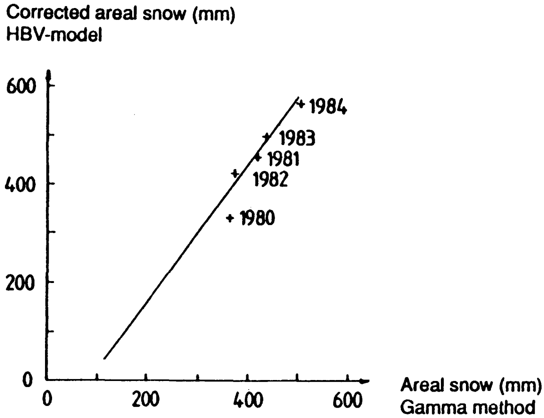

Fig. 3. Comparison between the areal snow water equivalents measured by the HBV model and the gamma method in the Kultsjön basin (Bergström and Brandt 1985).

The evaluation of the gamma radiation technique was based on the snow pack that was modelled by the HBV model, with correction for the volume error observed over the melt period. This was considered to be the most accurate estimate possible of the basinwide snow pack on the data of measurements. A comparison between the areal snow water equivalent estimated in this way and by the gamma method is shown in Fig. 3.

This relationship was used to correct the spring flood simulations by the HBV model for the period 1980-1984, Table 1. Although the data set was not independent as the same years had been used to derive the relationship, the results indicated a potential for improvements of the forecasts. The mean absolute error dropped from 30 mm to 19 mm and the improvement was especially noticeable after winter with unusual snow distribution, such as 1982.

The conclusions from the gamma radiation project can be summarized as follows:

Table 1 – The effect of snow corrections from gamma-measurements on the simulated volume error over snowmelt season, Kultsjön basin

Year	Volume error (mm)	Volume error with correction (mm)
1980	+ 20	+ 42
1981	+ 5	+ 1
1982	− 90	− 34
1983	− 31	− 16
1984	− 5	+ 4
Mean abs error	30	19

- The airborne gamma radiation technique has an obvious potential for estimating the snow pack in basins larger than 100 km^2.
- The results are particularly sensitive to variation in background activity caused mainly by daughter products of radon and cosmic radiation. (The background counts were determined by flying over the Lake Kultsjön before and after each pass).
- The repeatability of results of gamma radiation snow surveys is good.
- Verification against observation on the ground is difficult as the gamma technique measures a rather diffuse band with a width of approximately twice the flying altitude and with a variation of the relative contribution to the sensors. It was found that any comparison with ground measurements must be based on average values over at least 2 km. Areas with shallow snow cover – as in rugged terrain – will dominate, leading to an underestimation.
- The project has not been able to answer the important question of the upper limit of snow pack that can be observed by airborne gamma radiation technique, but we have a general feeling that, with this equipment, flight altitude, and in this area with fairly low natural radiation, the precision drops markedly when the snow water equivalent exceeds 600-800 mm.
- Results are convenient for updating the snow water equivalent in a runoff model before melting starts. Even a relatively dense network of flight lines, as in the Kultsjön basin (125 km of lines over 1,100 km^2), requires an empirical correction to arrive at basin snow storage.
- The costs are high compared to conventional hydrological forecasting by conceptual models based on observed precipitation and therefore most suitable where the precipitation network is very sparse and not representative.

The experiments with the gamma radiation ended after 1984 because the benefit from improved forecast did not justify the high costs involved.

Snow Measurements with Georadar

Parallel to the experiments with the gamma radiation technique in the Kultsjön basin a 900 MHz georadar was tested (Ulriksen 1982).

The method gives the time delay through the snow pack that has to be converted to water equivalent through calibration. For mountainous areas a constant factor (0.045 m/ns) is used to convert the time delay into snow water equivalent (mm). This factor is lower for forested areas and not constant. At the first test in 1982 the radar equipment was installed in the cabin of a tracked snow vehicle, later in a snowmobile and from 1985 in a helicopter.

A test with short-pulse radar installed in a helicopter was used to determine the

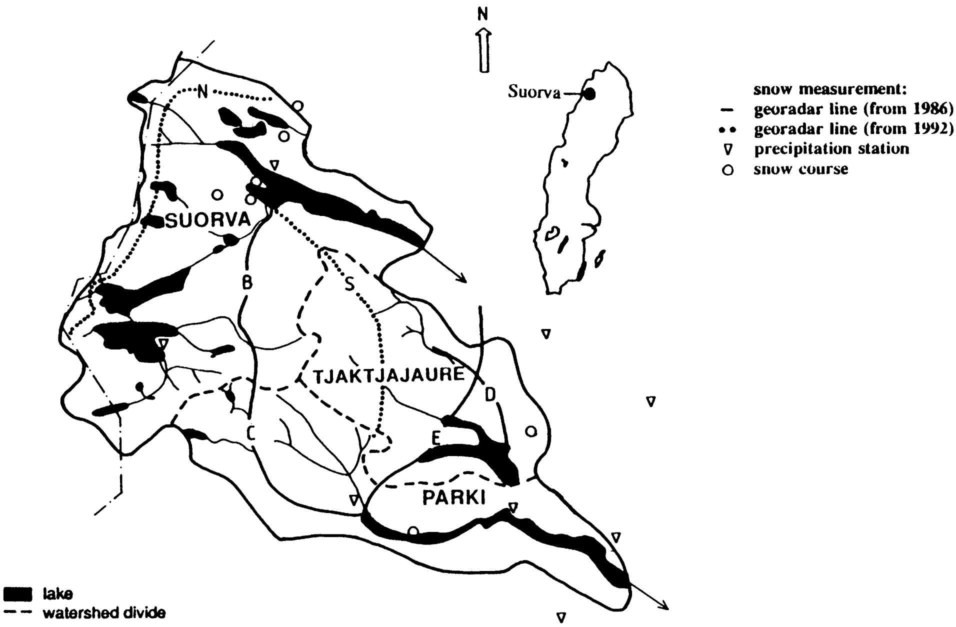

Fig. 4. The flight lines for georadar measurements, precipitation stations and snow courses in the upper part of the River Luleälven.

snow storage during 1986 to 1990 in the upper part of the River Luleälven (Brandt 1991). The georadar has been running to improve the hydrological forecasts in three sub-basins since 1992.

The lines flown from 1992 are shown in Fig. 4. The distance is 320 km that can be flown in one day if the weather is fine. The lines, B, C, D, and E were flown all years. Lines N and S are new since 1992 to better cover the high altitudes and western parts. The area is divided into different sub-basins for which the HBV model has been set up. During the test period 1986 to 1990 there were four lines more (180 km) that covered two other sub-basins (forested), but the results from them during the test period did not improve the hydrological forecasts so they were abandoned. The georadar method proved to work better in the mountainous areas above the timber line. The mountain basins studied (since 1992) are Suorva (4,862 km^2), Tjaktjajaure (2,267 km^2) and Parki (2,596 km^2).

One way to utilize the information from the georadar is to calculate the relationship between the snow pack, measured by the georadar along lines in the sub-basins, and the snow pack measured by the HBV model (corrected after the snowmelt season) the actual day. If this relationship is stable during a test period of some years it can be used in the future to update the snow storage in the model. In Table 2 the relationships and the mean values for the three sub-basins are shown. Line B is used for sub-basin Suorva (later also line N and part of line S can be

Table 2 –Relationship between snowpack calculated by the HBV model (corrected for volume error during the snowmelt season) and snowpack according to georadar measurements in Suorva, Tjaktajaure and Parki basins

Relationship/Year	1986	1987	1988	1989	1990	Mean value
Suorva	2.08	1.99	2.05	2.04	2.01	2.03
Tjaktjajaure	1.32	0.92	1.44	1.14	1.16	1.20
Parki	0.95*)	0.69	0.74	0.90	0.92	0.84

*) Georadar line C is missing.

used), lines B, D and E for Tjaktjajaure (later parts of line S) and lines, B, D and part of line E for Parki.

In Table 3 the volume errors are shown if the model is run with or without updating with georadar measurement calculated in the Suorva basin. Note that only results from 1992 and 1993 are independent. The updating with georadar will improve the results in the Suorva basin six years of seven, in Tjaktjajaure and Parki five and four years of seven respectively.

The conclusions from the applications of the georadar in the upper part of the River Luleälven are as follows:

- The method has been found suitable for updating the snow pack in the model for mountainous but not for forested areas.
- A test period of some years is required to find the empirical corrections that are needed.

Table 3 – The effect of snow corrections from georadar measurements on the simulated volume error over snowmelt season in the Suorva basin

Year	Volume error (1.5-31.8) (mm)	Volume error with georadar correction (mm)	Snowpack (mm)
1986	+ 51	− 17	621
1987	− 31	+ 12	591
1988	− 34	− 7	651
1989	+ 24	− 7	1067
1990	+ 12	+ 8	942
1992 independent	+ 115	+ 107	800
1993 years	− 117	+ 78	1049
Mean abs error	55	34	

As the georadar method is more robust and does not require a sophisticated installation in an airplane it has been found more suitable for operative use than the gamma radiation technique. It is now used operationally by the hydroelectric power industry in the upper part of the River Luleälven.

Snow Mapping from Satellite Imageries

Three types of satellite information have been tested by the SMHI. In 1987 we ordered SPOT imageries covering the Kultsjön basin during the snowmelt period, but it failed due to too much cloud at all passages. A test with Landsat TM in the same area also showed problems with cloudiness. It was found that Landsat or SPOT imageries could be useful for calibration but not for near real-time use (Moberg and Brandt 1988).

Satellites of the NOAA series provide a better opportunity to obtain cloud-free images since the area is scanned several times each day. The spatial resolution for NOAA satellites is only 1 km so basins smaller than some 200 km^2 cannot be evaluated. The NOAA imageries are automatically classified into different types of clouds and areas covered by water, ice, snow, and bare snowless grounds at the SMHI (Karlsson and Liljas 1990). They have been tested for snow mapping in seven basins starting in 1989 (Brandt and Moberg 1990). The main disadvantage of satellite data is that it gives the snow cover but not the snow water equivalent. Relationships between the snow cover from the satellites and the snow storage in the HBV model are calculated and the expectation is that these relationships will be a support for updating the HBV model. The advantage is the relatively low costs. Satellite information seems to be most suited for mountainous areas where there is no vegetation that hides the ground.

The attempts to use satellite information are still ongoing at the SMHI. Although satellites are used in this respect internationally, the applications in Sweden have not been anything but subjective but it is hoped that the information will be more valuable in the future when more geographically distributed hydrological models are developed.

Conventional Snow Courses

Traditionally snow course data are not generally available in Sweden. Two exceptions are records from the upper part of the River Luleälven and the River Klarälven. The ten sites in Luleälven are located above the timber line and were used in an attempt to improve the hydrological model results for five sub-basins. The results were discouraging, mostly due to very variable snow accumulation conditions. It was simply not possible to improve the hydrological model with this extra information.

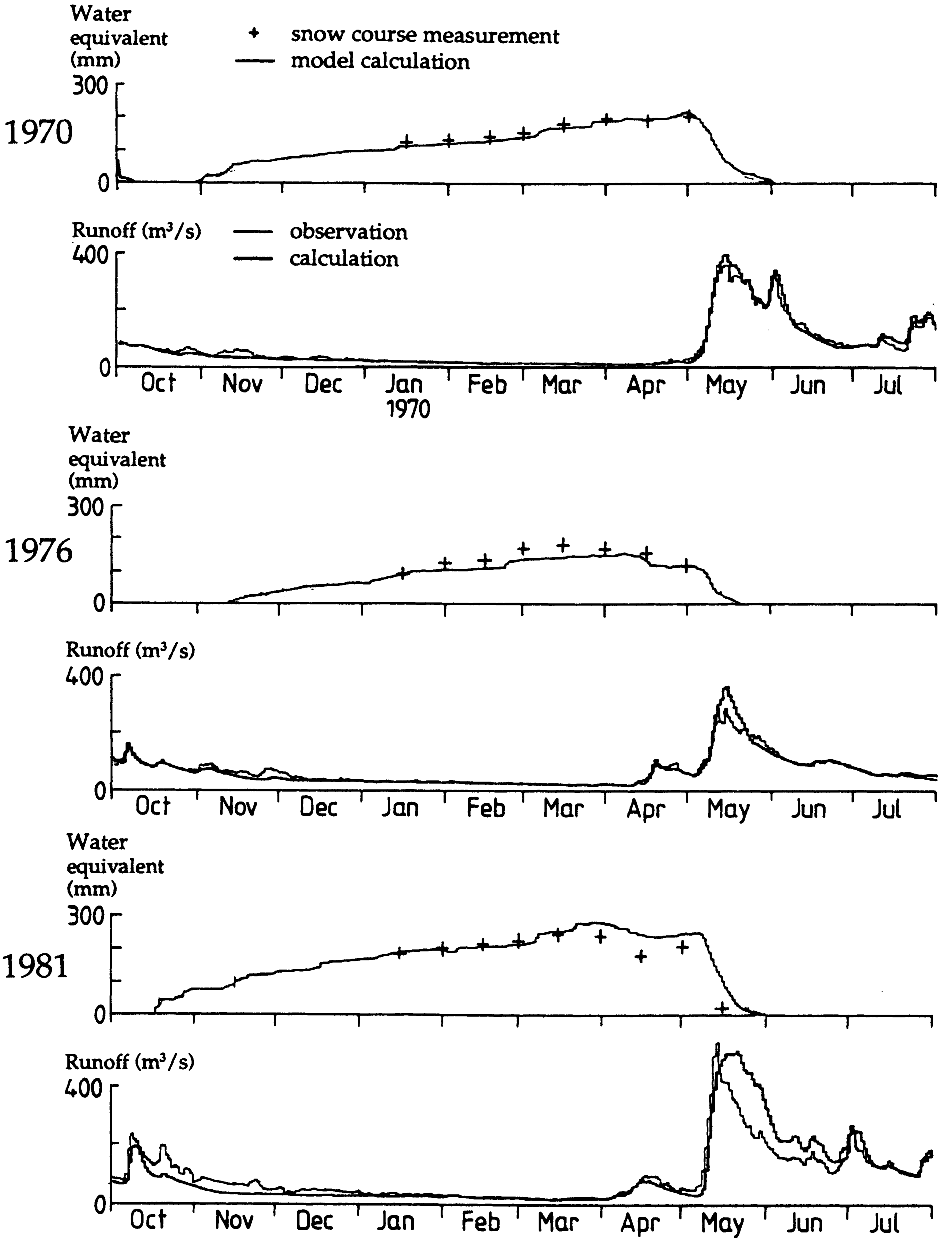

Fig. 5. Model simulations and measurements of snow water equivalent and runoff for the years 1970, 1976 and 1981 in the Trysilelva basin, the River Klarälven.

The six sites in the River Klarälven are located below the timber line and the avarages of the observations at the sites agree well with the simulated snow pack of the HBV model (Fig. 5). The Figure also shows the observed and simulated inflow to the Höljes reservoir. It is obvious that the model error would have been reduced after snow updating the year 1981. There are, however, other years when the updating would give the opposite results.

The overall conclusion is that we have found it questionable whether there is any extra information in the snow course data that may be used to improve the model simulation in the basins tested.

Conclusions

The conclusions from the different areal snow pack monitoring projects in larger basins are that these techniques have their greatest potential in areas where the climatological data coverage is poor, such as in the mountains.

Both gamma and georadar techniques require an empirical correction to arrive at a basin snow storage even with a relatively dense network of flight lines. The cost to integrate airborne gamma radiation technique into operational forecasting is high. It is lower for georadar and has been in operation in Sweden for three sub-basins since 1992. In the basins studied it seems to be difficult to integrate snow measurements from conventional snow courses into operational forecasts.

The integration of areal field data requires persistence. The hydrological models normally do very well under usual snow distribution conditions. Therefore the benefit from the extra sources of information provided by field data will not be obvious every year, maybe only when snow distribution is unusual.

To make full use of additional data we need to modify the existing hydrological models. If they are more fully distributed, in a geographical sense, it will be easier to update the snow pack.

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