

THE ENERGY BALANCE METHOD – A LITERATURE REVIEW

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The Energy Balance Method – A Literature Review

**A COMPARISON OF ENERGY BALANCE SNOWMELT
MODELS TO THE DEGREE-DAY MODEL**

ODDBJØRN BRULAND

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Energiforsk AB | Phone: 08-677 25 30 | E-mail: kontakt@energiforsk.se | www.energiforsk.se

Foreword

The semi-distributed hydrological model HBV, used for inflow forecasting by most actors in the Scandinavian hydropower, utilizes the temperature-index based degree-day method for computation of snowpack dynamics. This method has been proven to be applicable and effective during normal weather conditions and over longer periods of time, but it is well known that its processes concerning snow melt and refreezing can be underestimated or overestimated under certain weather conditions. Historically, tests using more physically based energy balance approaches in the Scandinavian operational models have not shown significant improvements. However, the progress in development of distributed models, as well as the quality and availability of input data, could give new possibilities for more accurate simulation of the snowpack.

Most applications for inflow calculation, used by river regulation agencies and hydropower companies in Scandinavia, are built upon the HBV model's infrastructure. It has long been discussed about improving the simulation of the snow dynamics by moving towards more distributed inflow models adapted to gridded data and energy balance methods, but an introduction of new models is a challenging task that would need significant resources. Several projects have been conducted to investigate these approaches, though, most of them within the framework of the currently used operational models and with little to no success.

Looking forward, with increased computational power, the development of hydrological models is continuously progressing, as well as meteorological models with higher resolution, providing simulated weather data with parameters needed for energy balance methods. HUVA (*Energiforsk's* program for hydrological development for the Swedish hydropower industry) has commissioned this literature study to get an overview of the state-of-the-art in this area, and to explore potential implementations of energy balance methods for inflow forecasting. The report provides an update on the current knowledge in the area and evaluates the potential of energy balance models using the commonly used degree-day method as a benchmark. In addition, it outlines the necessary requirements on model structure and input data for successful implementation of energy balance methods for inflow forecasting.

The HUVA-group thanks Oddbjørn Bruland, Norwegian University of Science and Technology, for an excellent overview that will be most useful in coming discussions on the future development of inflow models for the hydropower industry.

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This study is an evaluation of snowmelt models relevant for inflow forecasting for hydropower scheduling with a focus on comparison against the degree-day model which presently is most common among the hydropower producers.

The complexity of the snowmelt calculation can vary from full solution of the energy balance to only using one or more, more or less representative, temperature observations for the catchment and a calibrated threshold temperature and degree-day factor for the snowmelt. All studies investigated find that including elements from the energy-balance model one way or another improves the snowmelt calculations compared to the simple degree-day model. The major improvements are visible on the diurnal variation of snowmelt. Diurnal variation of inflow becomes more significant with smaller catchment and more important with less regulation possibilities and to predict the inflow to the unregulated part of the catchments. The better control of the inflow the higher the producer can allow the water level to be in the reservoirs and the better they can adapt the production strategy to price variations and to balance unpredictable wind energy. Thus, the inflow variation becomes more important in a more volatile energy market.

Most studies find the largest improvements by including variation of solar radiation. But it is also recommended to include estimates of longwave radiation as this can strongly impact the timing of the snowmelt and condensation as this can be the source to significant release of latent heat in the snowpack under specific condition and thus lead to significant melt events. How this can be done depends on the availability of data. The simplest approach does not need any other information than the degree-day model already uses. But today's weather forecasting models produce all the necessary input to these snowmelt models for any region in Scandinavia at the necessary temporal and spatial resolution. Even without any validation this will improve the snowmelt calculation compared to a simple degree-day approach. Combined with some validation data from local observations potential errors in the weather forecast can be avoided. Even this uncertainty is low and probably lower than the uncertainty related to extrapolation of observed temperatures to the highest altitudes in a hydropower catchment.

Both in respect of the variability of the snow cover depth, the variability of vegetation and the variability of radiation it is recommended to implement distributed models for in particular snowmelt inflow forecasting. Distributed inflow models also improve the ability to handle each intake or sub-catchment and diversions individually. This is a great advantage in the hydropower production planning or the scheduling process. Distributed models also open for a range of other features that can improve the hydrological forecasting and the water resource management in the hydropower systems. This is partly done by Statkraft and more companies are following their examples. Statkraft is using the open source tool Shyft which is a version of the ENKI that was developed at SINTEF and is also open source.

The computational issues are simply not an issue with today's computers. The major issue in respect of computation is the system robustness and data handling. This is independent of the modelling system and the major cost of transition to a new system.

As done in the Norwegian Meteorological Institute's project StrållInn, in a transition to energy balance based models, studies of the input variability and what influences this variability could be recommended for the research community. Even if this to a large degree is handled in the weather forecast models, validation from observations and methods for mixing forecast and observation can increase the reliability of the inflow forecasts.

Keywords

Snowmelt, Degree-day model, Energy balance model, Hydropower, Inflow forecasting

Sammanfattning

Denna studie är en utvärdering av snösmältningsmodeller som är relevanta för inflödesprognos för vattenkraftsplanering med fokus på jämförelse mot graddagsmodellen som för närvarande är vanligast bland vattenkraftsproducenterna.

Komplexiteten i snösmältningsberäkningen kan variera från full lösning av energibalansen till att endast använda en eller flera, mer eller mindre representativa temperaturobservationer för avrinningsområdet och en kalibrerad tröskeltemperatur och graddagsfaktor för snösmältningen. Alla studier som undersökts visar att inkludering av element från energibalansen på ett eller annat sätt förbättrar snösmältningsberäkningarna jämfört med den enkla graddagsmodellen. De stora förbättringarna är synliga på den dagliga variationen av snösmältningen. Dygnsvariation av inflödet blir mer betydande med mindre avrinningsområden och viktigare med mindre regleringsmöjligheter och att förutsäga inflödet till den oreglerade delen av avrinningsområdena. Ju bättre kontroll av inflödet desto högre kan producenten låta vattennivån vara i magasinen och desto bättre kan de anpassa produktionsstrategin till prisvariationer och balansera oförutsägbar vindenergi. Därmed blir inflödesvariationen viktigare i en mer volatil energimarknad.

De flesta studier finner de största förbättringarna genom att inkludera variation av solstrålning. Men det rekommenderas också att inkludera långvågsstrålning eftersom detta starkt kan involvera tidpunkten för snösmältningen och kondenseringen eftersom detta kan vara källan till betydande smälthändelser. Dagens väderprognosmodeller producerar all nödvändig input till dessa snösmältningsmodeller för alla regioner i Skandinavien med den nödvändiga tidsmässiga och rumsliga upplösningen.

Både vad gäller variationen i snötäckesdjupet, vegetationens variabilitet och strålningens variation rekommenderas att implementera distribuerade modeller för framför allt snösmältningsprognos.

Beräkningsproblemen är helt enkelt inte ett problem med dagens datorer. Den stora frågan när det gäller beräkning är systemets robusthet och datahantering. Detta är oberoende av modelleringssystemet och den stora kostnaden för övergången till ett nytt system.

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1 Background

On behalf of Energiforsk's Hydrological Development Programme, HUVA, a review of methods for calculating snowmelt in hydrological models for the hydropower industry has been carried out.

Snowmelt forms a significant part of the inflow to the hydropower industry's power plants. In a market characterized by increasingly unregulated power, unpredictable demand for energy and varying needs for regulated hydropower, it is becoming more important to be able to predict the inflow to power plants both with and without reservoirs in order to optimize production plans.

In that context, an assessment of methods for calculating snowmelt has been made through a literature study. Search and systematization algorithms developed at NTNU by PhD student Elhadi Mohsen Hassan Abdalla were used as well as studies refereed in previous publications.

In the literature study, a search was made for publications with the topic within modelling snowmelt, methods for calculating snowmelt and comparison of methods. A total of 220 publications were tracked down and of these 86 were found to be relevant.

In this project, the main focus is a comparison between the simple degree-day model that is traditionally used in HBV and various variants of more physically based energy balance models. The energy industry's need for continuous updating of inflow forecasts requires continuous access to input data and a robust model system. Very few studies have this as a criterion. Most studies refer to point locations, or small and often artificially defined areas and campaigns with extensive measurement schemes. Few of the studies include the simple degree-day model but make thorough evaluations of different variants of energy balance modelling. Among these are some that evaluate variants of the degree-day model including elements from the energy balance.

This report shall attempt to provide:

- a comparison between the energy balance method and actual water balance to provide an indicative answer to the accuracy of the model and its challenges.
- definition of requirements for input data, methodology and time resolution to ensure an implementation of the energy balance method that gives satisfactory results compared to the degree-day model.
- a comparison of implementation experiences between the energy balance method and empirical models, including different versions of the degree-day model, regarding their ability to describe the snowmelt rate in runoff models.
- recommendations regarding measurements to optimize the method's implementation.
- recommendations regarding the use of result data from meteorological models to optimize the implementation of the method.

2 Snowmelt and Runoff

Modelling the snowmelt itself can be done in many ways. The simplest method relates only to the air temperature

$$M = C_{x1} \cdot T_a$$

where M is snowmelt in mm water and C_x (mm/deg) is degree-day factor and T_a (°C) is observed air temperature. Although the melting is strongly correlated to the air temperature, due to solar radiation in particular, but also latent heat, you could experience snowmelt at temperatures below 0°C (Liston et al., 1999) and it does not necessarily melt at higher temperatures due to long-wave radiation. By introducing a threshold temperature, one can partially compensate for this.

$$M = C_{x2} \cdot (T_a - T_t)$$

where T_t is the threshold temperature for snowmelt. This is the variant of the degree-day model that is usually implemented in the HBV model. C_x and T_t are both subject to calibration. In addition to including elements of energy balance, the calibration of T_t will also be able to correct for the representativeness of the temperature observation.

The degree-day model can be expanded with various components from the energy balance such as radiation where albedo is also taken into account (Sand, 1990)

$$M = C_{x3} \cdot (T_a - T_t) + C_r \cdot (1 - a)R_i$$

where C_r depends on cloud cover, a is the albedo which is a function of days since the last snowfall and R_i is incoming solar radiation or the extra-terrestrial radiation which depends on location, time of year and day.

The model can gradually be expanded with more links and approaches to a full energy balance calculation.

$$Q_m + Q_i = Q_{sh} + Q_{lo} + Q_h + Q_e + Q_g + Q_r$$

where

- Q_m = energy available for melting snow (W/m²),
- Q_i = change in the snow pack's internal energy (W/m²),
- Q_{sh} = net shortwave radiation (W/m²),
- Q_{lo} = net longwave radiation (W/m²),
- Q_h = sensible heat (W/m²),
- Q_e = latent heat (W/m²),
- Q_g = heat flux from the ground (W/m²),
- Q_r = heat from precipitation (W/m²).

Shortwave radiation depends on direct and indirect shortwave radiation from the sun. This depends on the sun's position in the sky, in other words the time of year and day, on the state of the atmosphere and cloud cover which absorbs, reflects, and scatters the sun's radiation and contributes to diffuse radiation, and on the

terrain and vegetation which reflect the radiation. Shortwave radiation can be observed directly or approximated by information about time and place, cloud cover and the topography and surroundings.

The albedo, the reflectivity of the snow cover, determines how much of the solar radiation is absorbed by the snow. It varies from over 90% (90% reflected) for new fallen snow to under 60% for old snow. The albedo depends on many conditions and is very complex to model exactly but is largely dependent on the age of the snow cover and which processes the snow cover has undergone.

Longwave radiation depends on the temperature and state of the atmosphere. About 16% of the extra-terrestrial radiation is absorbed by mainly water vapor, ozone, carbon dioxide and dust in the atmosphere, and about 4% by clouds. This absorbed energy increases the temperature in the atmosphere and is emitted as long-wave radiation, some of which reaches the earth's surface. Incoming longwave radiation is usually calculated based on air temperature and humidity, or air temperature and a cloud factor (Ashton, 1986; Bengtsson, 1976; Harstveit, 1984; Male, 1981; Partridge & Platt, 1976; Sand, 1990; Swinbank, 1963; U.S. Army Corps of Engineers, 1956). According to (Male, 1981) the most quoted method was first proposed by Brunt (1952)

$$Q_{li} = \sigma T_a^4 (a + b\sqrt{e})$$

where σ = Stefan-Boltzmann constant, T_a = air temperature (K), e = vapor pressure (Pa) and a and b are empirical constants. Harstveit (1984) and Sand (1990) included the cloud cover and used a formula for Q_{li} according to

$$Q_{li} = k_{l1} \cdot \sigma \cdot T_a^4 + k_{l2} \cdot C_s + k_{l3}$$

where k_{l1} , k_{l2} , k_{l3} is empirical constants and C_s is the cloud cover. Outgoing longwave radiation is determined by Stefan Boltzmann's law

$$Q_{lo} = \sigma \cdot T_s^4$$

where T_s = surface temperature (K). Male og Gray (1975) have shown that accurate measurements/estimates of the snowpack's temperature are crucial for successfully calculating the energy balance for shallow snowpacks, and especially for the time of initialization of snowmelt (Kane et al., 1997). As the energy balance depends on the snow surface temperature and vice versa, numerical methods must be used to provide an exact solution to the energy balance.

Sensible and latent heat depending on temperature and the moisture gradient above the snow surface. The snow affects the air above it and the effect of high temperature and humidity gradients depends on how quickly the air is replaced. This is a function of the wind speed and the turbulence above the snow surface.

The various components of energy balance can be approximated and calculated in several different ways and with several levels of accuracy and complexity. Rutter et al. (2009) and Essery et al. (2013) have described and compared snow models of different complexity and together provide a comprehensive overview of different approaches to energy balance calculations.

The accuracy of the inflow calculation depends on more factors than the accuracy of the snowmelt model. Snow depth, snow distribution and terrain characteristics affect the intensity and duration of snow runoff to at least the same extent. The snowmelt affects how the amount of snow and the distribution of snow develop, but there is little joy in an advanced snowmelt model if the initial amount of snow and the distribution of snow are not sufficiently well described.

Although the hydropower producers normally carry out several snow measurements throughout the winter and have placed great emphasis on developing methods to describe both snow quantity and snow distribution, there are few studies that cover fields of relevant size, take a known snow quantity and snow distribution as a starting point and provide a good assessment of the snowmelt calculations regardless of the other factors.

3 Litterature Review

Of the 86 studies found through the literature search, there are 5 that stand out in relation to comparing the degree-day model with energy balance considerations. These are MacKay et al. (2018); Magnusson et al. (2011); Meeks et al. (2017); Oreiller et al. (2014); Skaugen et al. (2018a). These studies have been selected because they assess catchment areas with relevant sizes for the hydropower industry and they assess the effect of the energy balance, or an element from this in the degree-day calculations on the inflow. In addition to these, studies by Sand (1990) and Bruland et al. (2001); Bruland & Killingtveit (2002) are largely directed at hydropower's needs and challenges when choosing a snowmelt methodology.

MacKay et al., (2018) a study in a 22 km² ice-dominated sell-off field in Iceland. The purpose was, among other things, to compare three versions of the degree-day model, from only considering temperature and threshold temperature to including radiation, landscape effects, and albedo.

Magnusson et al., (2011) did a similar study for a partially wide-covered field in Switzerland of 9.9 km². Here, a full energy balance model in Alpine3D is compared with a degree-day model that includes a radiation factor (Hock, 1999).

Meeks et al., (2017) evaluates uncertainty in relation to runoff from a small but natural catchment in Switzerland simulated in a traditional and a modified version of the degree-day model and compares with energy balance calculations.

Oreiller et al., (2014) compares energy balance modeled in Crocus and a modified degree-day model to simulate the spring flood from a 244 km² field in Canada.

Skaugen et al., (2018a) compares 4 snow models in 17 fields in Norway with sizes from 30 to 3000 km². The models are a simple degree-day model, two modified degree-day models (DDD-EB and SeNorge) and a full energy balance model (Crocus).

Sand, (1990) evaluated different variants of the degree-day model against energy balance models in experiments in mountain areas, forest terrain and urban areas as well as on Svalbard

Bruland et al., (2001); compared standard and modified degree-day models with an energy balance model in Crocus in an area on Svalbard.

Bruland & Killingtveit, (2002); compared energy balance and degree-day models for a 30 km² and 50% glaciated field on Svalbard.

All of these studies conclude that energy balance or approaches to the energy balance model improve simulations of the inflow.

“This study shows that snowmelt model predictions can have considerable uncertainty, which may be reduced by the inclusion of more data that allows for the use of more complex approaches such as the energy balance method”, (Meeks et al., 2017)

“CROCUS clearly overestimated the SWE, likely as a result of not including loss in SWE because of blowing snow sublimation and relocation. To correct this, we included into

CROCUS a simple parameterisation effective after a certain wind speed threshold, after which the thermodynamic model performed much better than the traditional mixed degree-day/energy balance model.” (Oreiller et al., 2014)

“The energy-balance model provided accurate discharge estimations during periods dominated by snowmelt, but dropped in performance during the glacier ablation season. The glacier melt rates were sensitive to the modelled snow cover patterns and to the parameterization of turbulent heat fluxes. In contrast, the temperature-index model poorly reproduced snowmelt runoff, but provided accurate discharge estimations during the periods dominated by glacier ablation, almost independently of the method used to distribute precipitation. Apparently, the calibration of this model compensated for the inaccurate precipitation input with biased parameters.” (Magnusson et al., 2011)

“Increased model complexity is shown to improve acceptability when evaluated against specific signatures but does not always result in better consistency across all signatures, emphasising the difficulty in appropriate model selection and the need for multi-model prediction approaches to account for model selection uncertainty.” (MacKay et al., 2018)

“The snow simulations are validated against observed snow water equivalent (SWE) and against satellite derived snow covered area (SCA). SeNorge and DDD_EB perform best with respect to both SWE and SCA suggesting model structures suited for describing snow conditions at ungauged sites and for a changed climate.” (Skaugen et al., 2018b)

“This energy balance based HBV-model gives a better simulation of both snow and glacial melt. It was also found that estimates of sensible heat were improved by using a function with a non-linear wind speed dependency.” (Bruland & Killingtveit, 2002)

“The simulations were carried out for the melt periods in 1992 and 1996 as these two periods represent very different meteorological conditions. The results of these simulations exposed weaknesses in all the models. The energy balance model lacks calculation of cold content in the snowpack. This influences both the outgoing longwave radiation and the timing of the melt. Due to the effect of compensating errors in the simulations, CROCUS performed better than the simple energy balance model but also this model has problems with the simulation of outgoing longwave radiation. The temperature index model does not perform well for snowmelt studies in regions where radiation is the main driving energy source for the melt.” (Bruland et al., 2001)

“In this study the temperature index model with a separate term for short wave radiation combined with the two-linear-reservoir model with a dynamic response function (Model M3-T3) surprisingly performed almost as well as the energy balance model, $R^2 = 0.86$ and $R^2 = 0.87$, respectively.” (Sand, 1990)

Based on these conclusions and based on a direct comparison of the use of energy balance or an element of this against simpler degree-day models and supported by assessments from studies of snow models, better simulations of the inflow are obtained by including elements of the energy balance in the simulation of snowmelt.

On average and over longer periods of time (day/week to month), a simple degree-day model will work well. How well will depend on the climatic and topographical variability in the catchment area as well as the representativeness of

the temperature measurements. Over shorter periods of time (within the day and week), the variability in radiation over the day and season and the effect of the terrain, cloud cover and weather type will play a significant role. According to Magnusson et al. (2011) *“The temperature-index model displayed a flatter slope with a higher intercept than the energy-balance model. This indicates that fast discharge fluctuations were underestimated which suggest that over short time scales the melt rates might be influenced by single energy-balance terms not included in the model. Indeed, this is a known weakness of this model type (Husset al., 2008a).”*

Bruland (2001) also shows that it is not possible to make the same degree-day model work for a radiation-dominated snowmelt period and one dominated by sensible and latent heat. This is also clear from the figure from Hock, (2003) which shows that the degree-day factor goes down when sensible heat dominates and up where radiation dominates the melting.

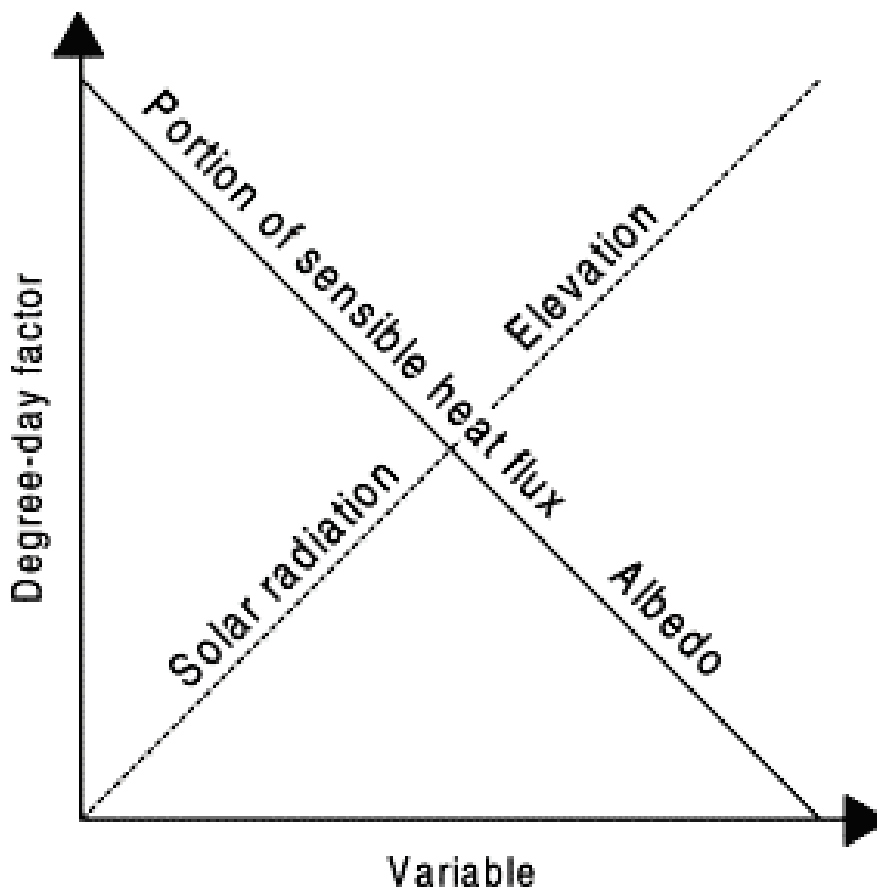


Figure 1. Degree-day factor in different situations (Hock, 2003).

Several of the studies highlight these effects of spatial and temporal variation as a main challenge for the degree-day model. These can be solved or improved as shown in, among others, these studies Bruland et al. (2001, 2002); Hock (1999); MacKay et al. (2018); Sand (1990); Skaugen et al. (2018b) and as recommended by Hock (2003). By including elements of the energy balance in the degree-day model without going to a full solution of the energy balance, one will remove or reduce major errors in melting events.

Traditionally, the HBV models used in the hydropower industry are only divided into altitude levels. This is not sufficient to take into account variation in radiation. The spatial variation in radiation in particular implies that the models must be spatially distributed to achieve the full effect of including radiation in the calculation. Skaugen et al. (2018a) and Bruland et al. (2002) nevertheless document that significant improvements are achieved by including elements from the energy balance also in a non-distributed model.

3.1 COMPARISON BETWEEN ENERGY BALANCE METHOD AND ACTUAL WATER BALANCE: ACCURACY AND CHALLENGES

The energy balance method is not an unambiguously described method. The most complex models such as Crocus (Brun et al., 1989) and SnTerm (Jordan, 1991) are fully physically models with layered snowpack and heat transport and heat storage in the snowpack. The accuracy of these models depends mainly on the input data. With observed short- and long-wave radiation, humidity, temperature, and wind speed at several levels as well as ground temperature and precipitation, all representative of the snowpack, these models will be able to give a very exact description of the snowmelt process.

This is unrealistic to achieve for remote, large catchment areas, preferably high up in the mountains, as is the case for the hydropower producers. In order to achieve good results for the inflow calculation with a full or partial energy balance model, one therefore depends on good estimates of the most important input values. The long-wave radiation is a challenge as this depends on the surface temperature of the snow and this in turn depends on the energy balance calculation (Male & Gray, 1975). This has a particularly large influence on the timing of snowmelt, as the snowpack must first reach melting temperature (Kane et al., 1997). This is solved in the complicated layered models, but can be challenging to estimate in simpler variants. Bruland et al., (2001) found an empirical approach based on snow thickness and temperatures in the precedent days that provided good adaptation to observed data from snow shafts through 7 melting seasons on Svalbard. During the melting period when the snow is isotherm at 0°C the challenge is reduced, but even then, on days with clear sky the emitted longwave radiation is high and can in particularly through the night and in shadowed areas, cool the snow and stop and delay the melting process and snowmelt runoff.

Longwave radiation from vegetation is another challenge addressed by Oreiller et al. (2014). Heat radiation from heated vegetation contributes to melting in its immediate area. This is one of the areas where energy balance models can be improved to provide a more accurate runoff from forested areas (Yang, 2008). With distributed models and vegetation maps, it is possible to approximate this contribution.

Wind speed largely affects sensible and latent heat. Wind strength can vary greatly over a large catchment area and often increases with height above sea level. This challenge is just as great in the degree-day model as this reflects sensitive heat in the energy balance model and is affected to the same extent by the wind strength.

Several studies use satellite data which, among other things, can give the cloud cover its characteristics and distribution, preferably combined with meteorological observations and model data which provide the necessary information for complicated energy balance simulations. Studies carried out by, among others Bellaire et al. (2011, 2013) and Luijting et al. (2018) show good results in simulating the amount of snow and snow-covered area throughout the snow season.

3.2 INPUT DATA, METHODOLOGY, AND TIME RESOLUTION FOR SATISFACTORY RESULTS

Input data will depend on the choice of model type. With a full solution of the energy balance as in Luijting et al. (2018), wind, temperature, precipitation and short and longwave radiation must be described. These data could be obtained from meteorological models. Such models exist with sufficient resolution in time and space for the whole of Scandinavia and will be available to the power industry. A simpler approach with a degree-day model extended with a radiation term provides an improvement in snowmelt and especially the variation over the day (Bruland et al., 2001, 2002; Sand, 1990; Skaugen et al., 2018a). Variation over the day can be of great importance for hydropower producers who report their production for every hour (and shorter) throughout the next day. The radiation can be calculated using calculated extra-terrestrial radiation and the cloud cover. The cloud cover can be estimated using the most simple approach where observed precipitation indicate full cloud cover, while no precipitation indicate clear sky (Skaugen et al., 2018a) or more detailed by using extrapolation or interpolation of nearby observations of radiation, or more directly from satellite observations of the cloud cover (Kolberg, 2018). Studies of how and how well radiation can be estimated is done by The Norwegian Meteorological Institute in the project Strållinn (Bakketun & Kristiansen, 2018).

If latent heat is included, as i.e. in the SSib model (Feng et al., 2008) it will also capture cases where condensation in the snow cover contributes to snowmelt. Also, this component can be included using a simple approach where precipitation indicate 100% saturated air. The efficiency of the condensation would then depend on exchange of the air above the snow surface or if there is wind or no wind. Estimation of humidity can also be done based on nearby relative humidity observations or taken from a meteorology model. Condensation can under specific conditions contribute to significant melt events and is recommended to take into account.

As previously documented through several studies, improvements in the snowmelt calculations will be achieved by the inclusion of an energy balance element. The most significant improvement is by taking into account the variation of radiation throughout the day and season, but with access to relevant data on the catchment scale, further improvements to the snowmelt simulation will be achieved by including the effect of longwave radiation and condensation.

If one is to take full advantage of the implementation of radiation-based melting models, and not at least the effect of gradually more scattered snow cover through

the melting season due to uneven snow distribution and uneven melt one should also use distributed hydrological models.

The advantage of energy balance-based models compared to a simple degree-day model is greatest with a time resolution shorter than a day. For the diurnal variation to be relevant, the models should have hourly intervals during the melting period.

A comparison of implementation experiences between the energy balance method and empirical models, including different versions of the degree-day model, regarding their ability to describe rate of snowmelt in runoff models has been answered initially in this review.

4 Recommendations

4.1 MEASUREMENTS TO OPTIMIZE IMPLEMENTATION

Several of the studies compare the models' performance from start of snow accumulation to the end of the snowmelt. A large part of the error in the simulations is due to errors in the accumulation period (snow amount and snow distribution). If the methods are to give the right result, it is crucial that the initial conditions are as correct as possible. This means that the snow model should include relevant redistribution of the snow and snow measurements and observations should be carried out that can validate and correct snow-covered area and give approximately real snow distribution in each grid cell.

Shortwave radiation measurements and relative humidity are recommended in addition to temperature, wind, and precipitation within the catchment area. The radiation measurements can be used directly or as an indication of cloud cover variation.

In addition to this, methods as demonstrated in Luijting et al. (2018) og Skaugen et al. (2018a) are recommended for the use of meteorological data in energy balance modelling.

4.2 USE OF RESULT DATA FROM METEOROLOGICAL MODELS TO OPTIMIZE IMPLEMENTATION

The author refers to the report from Met.no and Sintef, respectively, as well as the publication of Luijting et al., (2018) and Skaugen et al., (2018a).

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THE ENERGY BALANCE METHOD

– A LITERATURE REVIEW

This review is an evaluation of snowmelt models relevant for inflow forecasting for hydropower production. All studies included in this literature review find that including elements from the energy-balance model, one way or another, improves the snowmelt calculations compared to the simple degree-day model. The major improvements are visible on the diurnal variation of snowmelt.

Most studies find the largest improvements by including variation of solar radiation. But it is also recommended to include estimates of longwave radiation as this can strongly impact the timing of the snowmelt and condensation as it under specific conditions can be a source of significant release of latent heat in the snowpack, thus leading to significant melt events. In addition, in respect to the spatial variability of snow cover depth, vegetation, and radiation it is recommended to implement distributed models for snowmelt inflow forecasting in particular.

How this can be done depends on the availability of data and today's weather forecasting models produce all the necessary input to these snowmelt models for any region in Scandinavia at the necessary temporal and spatial resolution. The computational aspects of utilizing this data in the energy-balance model is also not an issue with today's computers. The major issue in respect of computation is the system robustness and data handling. This is independent of the modelling system and the major cost of transition to a new system.

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