Experience From Predictions in Ungauged Basins (PUB) in the Nordic Countries

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Contents

Preface

The International Association of Hydrological Sciences (IAHS) has recently initiated the Decade for Predictions in Ungauged Basins (PUB). PUB is a research initiative with the aim of reducing the uncertainty in hydrological predictions and forecasts in catchments where ground based observations are missing. Planning and management of water resources in the Nordic countries have often necessitated estimation of hydrological processes in ungauged basins, e.g. through the use of statistical techniques, hydrological models or remote sensing technologies. A working group with the aim of presenting an overview of the development within PUB was established in 2003 by the Chiefs of the Hydrological Institutes in the Nordic countries (CHIN). Results from this working group point to the conclusion that the national hydrological institutes of the Nordic countries have substantial experience with predictions and forecasts in ungauged basins from operational hydrology, and that methods within this field have been applied with good results.

Oslo, February 2005

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International Association of Hydrological Sciences (IAHS) organiserer forskningsinitiativet Decade for Predictions in Ungauged Basins (PUB). Formålet med PUB er å redusere usikkerheten i hydrologiske prognoser og beregninger i avrenningsområder hvor observasjoner mangler. Forvaltning og utnyttelse av vannressurser i de nordiske landene har ofte medført behov for estimering av hydrologiske prosesser i umålte avrenningsområder, for eksempel ved bruk av statistiske metoder, hydrologiske modeller eller fjernanalyse. En arbeidsgruppe med formål å presentere en oversikt over status i arbeidet med PUB i de nordiske landene ble satt ned av CHIN (Chiefs of the Hydrological Institutes in the Nordic countries) i 2003. Resultatet er presentert i denne rapporten. De nasjonale hydrologiske institusjonene i de nordiske landene har lang erfaring med hydrologiske prognoser og beregninger i umålte avrenningsområder og disse metodene har vært benyttet med gode resultater i operasjonell hydrologi.

1 Introduction

The need for large scale mapping and management of water resources has been the driving force behind the frequent use of hydrological models in the Nordic countries. For more than three decades, models of hydrological processes have been applied for various purposes, e.g. for planning the operation of hydropower production systems, streamflow forecasting and in connection with water quality issues. Although observations networks are dense compared to most developing countries, the need for determination of water budgets at different spatial and temporal scales across large regions has frequently required use of models in ungauged basins. A model is any method or algorithm that describes the processes of interest and their interactions. An ungauged basin is one with inadequate data to estimate the hydrological variables of interest to the required accuracy. For instance, a basin with continuous measurements of precipitation and runoff, but without measurements of the chemical constituents of streamflow is considered gauged with respect to the quantity of water, but ungauged with respect to water quality (Sivapalan et al. 2003a).

Although hydrological data are needed for water resources management, observation networks are declining in many parts of the world. The International Association of Hydrological Sciences (IAHS) has therefore initiated the Decade for Predictions in Ungauged Basins (PUB), a research initiative with the aim of providing hydrological data where ground based observations are missing. PUB is defined as predicting or forecasting the hydrological response of ungauged basins to meteorological input, i.e. before it happens. Processes of interest can be, for example, precipitation, streamflow, latent and sensible heat fluxes, soil moisture content, groundwater flow, snow, sediments and water quality, so every basin is ungauged in some respect. The predicted hydrological response can be a continous time series of the process of interest, or statistical measures of its variability in space or time, including extremes (Sivapalan et al. 2003a).

The PUB programme contains several scientific objectives, including new data collection strategies and advancement of existing theories and models, but only a few of these approaches have been applied extensively in the Nordic countries: (1) Extrapolate from gauged basins using systematic approaches to predict catchment functioning based on an interpretation of the observed response obtained at the catchment scale; (2) Simulate with process-based hydrological models. Many models require meteorological inputs that drive the basin response. Characterizing this input at different temporal and spatial scales is usually a requirement for performing predictions or forecasts in ungauged basins. Furthermore, remote sensing technologies have the potential for providing measurements of input data and state variables with complete spatial coverage, although these methods are unable to perform predictions or forecasts.

This work presents results from a working group with members from Finland, Iceland, Sweden and Norway established by the Chiefs of the Hydrological Institutes in the Nordic countries (CHIN). The purpose is to provide an overview of the experience obtained from operational hydrology in these countries with methods which have been used or have the potential to be used for predictions or forecasts in ungauged basins. A summary of results from selected studies is presented.

2 Systematic approaches to transfer of information at the catchment scale

Systematic approaches which involve interpreting or learning about a catchment's functioning from data obtained at the catchment scale or from patterns in the observed data are often termed downward approaches (Sivapalan et al. 2003b). Examples of these approaches involve extrapolation from gauged basins using regionalization methods combined with statistical information transfer, and methods for characterizing space and time variability at multiple scales.

Regionalization with the purpose of transferring information from one site to another was used for estimating flood frequencies in ungauged basins in Norway by Sælthun (1997). Homogeneous regions were determined by cluster analysis and normalized flood distribution curves for all catchments within a region were constructed by scaling individual floods by the mean annual flood. Regression equations were used for individual basins in order to relate mean flood to mean annual runoff and catchment characteristics that represent flood generating mechanisms. Krokli (1988) used multiple regression to estimate low-flows characteristics as a function of catchment physiography and mean annual runoff. Andersen et al. (1983) used regression equations for estimating the parameters of a conceptual precipitation-flood model based on catchment characteristics. Hisdal and Tveito (1992) generated runoff series at ungauged locations using empirical orthogonal functions for constructing a global set of functions describing temporal and spatial runoff variations. A kriging procedure improved the results by including the influence of altitude in the spatial functions. Bogen and Bønsnes (2003) estimated sediment yield in ungauged glacierized areas using results from long-term measurements which revealed that erosion rates to a large extent are controlled by bedrock geology and glacier characteristics, while sediment export for individual years is controlled by meteorological conditions.

In the cold regions of the world, floods may be caused by a variety of processes involving interactions between rainfall, temperature, snow and ice. Snorrason et al. (2000) classified different flood phenomena in cold regions and described the characteristics of watersheds prone to each flood type as well as supplying key equations describing the processes involved. Where glaciers are dominant, the melting season consists of one continuous flood with extreme events provoked by high temperature rather than precipitation. An example of this is shown in Fig. 1 where the discharge of the river Jökulsá á Dal in the summer of 1991 is compared to records of temperature and precipitation. Since Icelandic rivers have variable watershed characteristics with regards to glacier and groundwater components their response to climatic long-term variability varies.

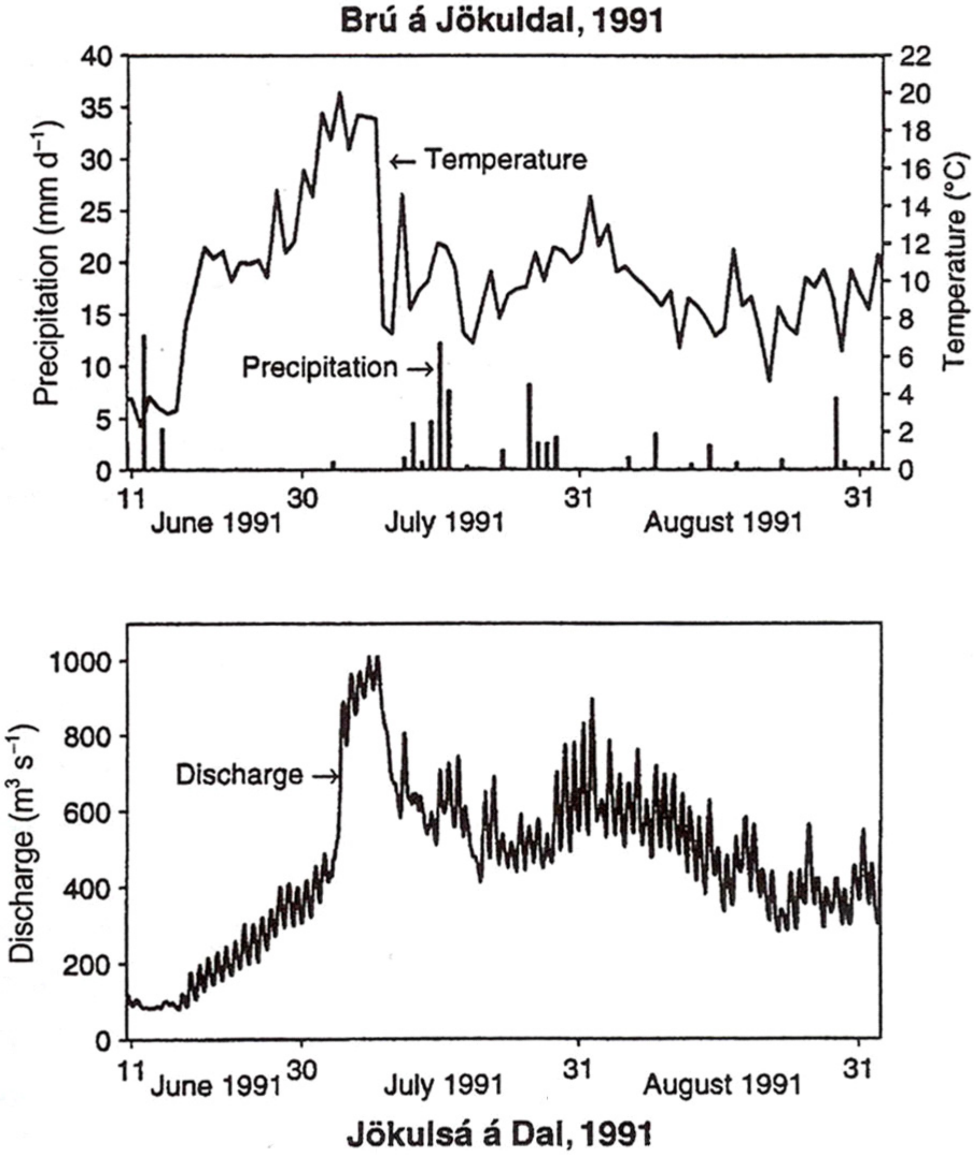


Figure 1. Extreme melting flood in the river Jökulsá á Dal, Iceland 1991.

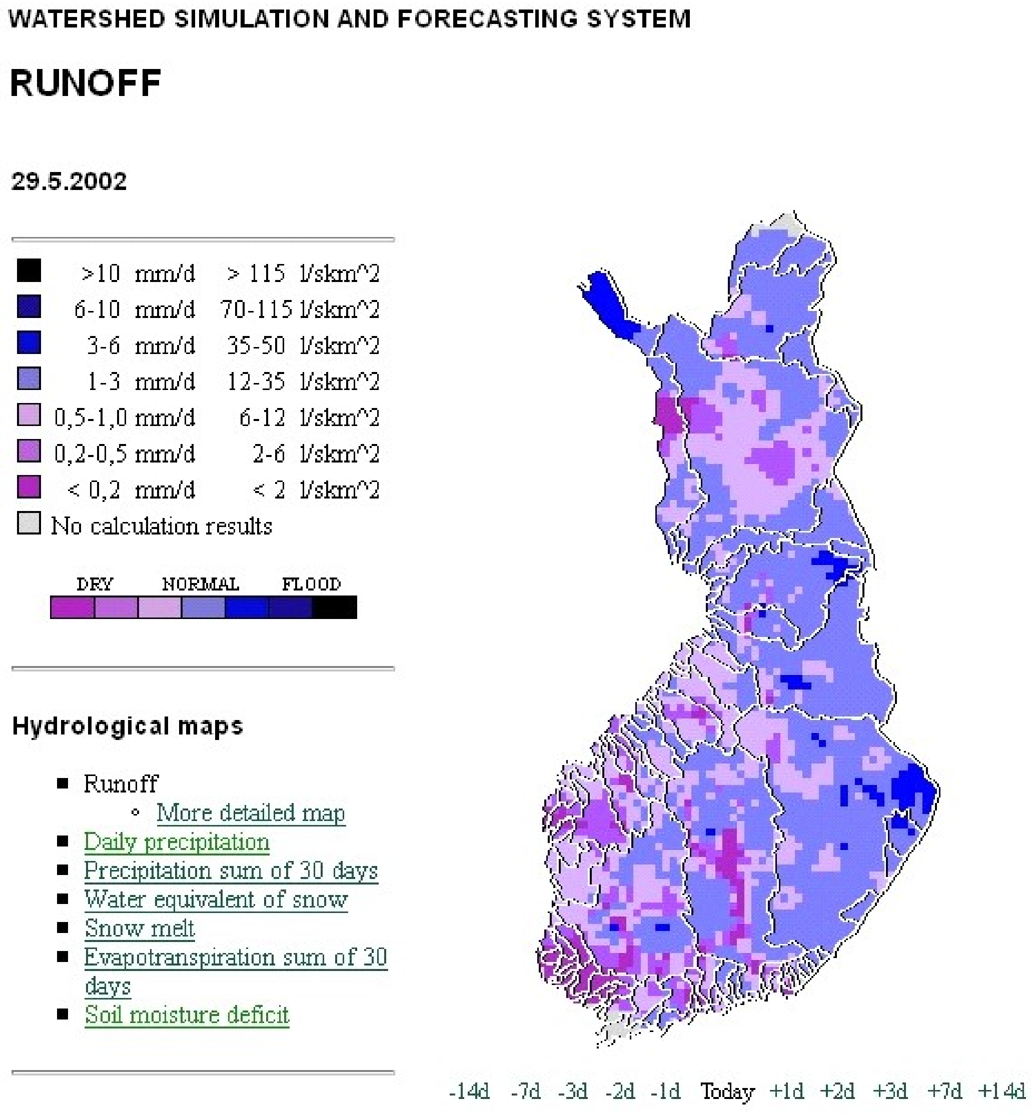
The variability in some Icelandic river flow time series has been compared to gridded mean sea level pressure and indices of atmospheric circulation such as the North Atlantic Oscillation (NAO) (Snorrason 1999, Jónsdóttir et al. 2004). Further studies of long-term variability of streamflow is being carried out at the Hydrological Service, National Energy Authority of Iceland and can be extended to ungauged basins through classification of watersheds. A similar approach is being applied by Tveito and Roald (2004), who have related large-scale atmospheric circulation patterns to the spatial distribution of discharge using principal components analysis of gridded mean sea level pressure data. The regional relations between runoff response and different circulation types will be used to assess future frequencies of runoff anomalies in ungauged basins by addressing changes in circulation patterns based on scenarios from atmosphere-ocean general circulation models.

Another approach to learning from data is the study of hydrological functioning at several scales. Scale refers to a characteristic length or time of a process. Gottschalk and Tveito (1997) presented a procedure for interpolation and spatial disaggregation of annual runoff to a grid network applying an objective method. The method, which accounts for runoff as an integrated process following the river network, was applied to an area of 17000 km^2 in south-east Norway. The derivative of flow with respect to the length coordinate along the rivers was interpolated, adding the additional constraint that lateral inflow is balanced with observed runoff. Skaugen and Væringstad (2004) presented a method for estimating flood quantiles in a homogeneous region based on spatial scaling of discharge. Scaling is understood as the effect of changing the scale (aggregation or disaggregation) of the hydrological quantities in question.

3 Simulations with process-based hydrological models

Conceptual and physically based models describe the relationship between meteorological inputs or other boundary layer conditions and the hydrological system using process-based model equations derived from principles of thermodynamics and fluid mechanics, or from simplified, but plausible conceptual representation of the processes of interest. This upward approach to hydrological modelling attempts to predict large-scale response by scaling up the mechanistic process understanding from small temporal or spatial scales (Sivapalan et al. 2003b). In order to perform predictions or forecasts in ungauged catchments, some sort of extrapolation or transfer of model structure and model parameters is required. Furthermore, future factors which influence the hydrological processes under consideration must be estimated. The most important future factors are meteorological input data and information about land use.

The Watershed Simulation and Forecasting System (WSFS) operated by the Finnish Environment Institute (SYKE) provides simulated hydrological data for gauged and ungauged basins in Finland (Vehviläinen and Huttunen 2002). Available variables are discharge, runoff, precipitation, temperature, snow water equivalent, evapotranspiration, lake evaporation, lake inflow and outflow, soil moisture and groundwater storage. Simulated spatial data are available from first level basin division (scale 1000-10000 km^2) down to third level division (10-100 km^2). Discharge is simulated at the outflow points of sub-basins (5000) and lakes (2500) (Fig. 2). The hydrological model of WSFS is a distributed version of the HBV model (Bergström 1995) further developed at SYKE (Vehviläinen 1994; Elo and Koistinen 2002; Jauja et al. 2002). The geographical information included in WSFS is sub-basin hierarchy with area, elevation model, lakes over 1 km^2 with area and depth data, lake and river network, river length, width and slope, land use as forest, field and marshland percentage. Process parameters are calibrated against all available data over Finland: discharge, water level, snow line measurements, satellite information of snow coverage and lake surface temperature. Calibrated parameters are transferred to ungauged basins via ‘model interpolation or extrapolation’: Above a discharge observation point or between two discharge observation points the basic process parameters of sub-basins are kept nearly the same; for each parameter there is a maximum difference between adjacent sub-basins. The available geographical data take into account the specific characteristics of all sub-basins. The water balance of the aggregated ungauged sub-basins is kept correct by calibration against the nearest available discharge observation point. If there are no discharge observations in a basin, the basic parameter set of the nearest gauged basin is used together with the geographical data. Thus WSFS simulates hydrological processes in gauged and ungauged catchments for the whole of Finland with reasonable accuracy. The simulations can be checked by extra measurements of discharge, water level or snow water equivalent to verify the reliability of the results. These simulated data are used for yearly reports and planning of water related issues made by local water authorities and consultants, etc.



WATERSHED SIMULATION AND FORECASTING SYSTEM

RUNOFF

29.5.2002

■	>10 mm/d	> 115 l/skm^2
🟦	6-10 mm/d	70-115 l/skm^2
🟦	3-6 mm/d	35-50 l/skm^2
🟦	1-3 mm/d	12-35 l/skm^2
🟪	0,5-1,0 mm/d	6-12 l/skm^2
🟪	0,2-0,5 mm/d	2-6 l/skm^2
🟪	< 0,2 mm/d	< 2 l/skm^2
☐	No calculation results	

Figure 2. Runoff map of the Finnish Watershed Simulation and Forecasting System, available at http://www.environment.fi/waterforecast.

The MBT degree-day glacier mass balance model (Jóhannesson 1997) uses temperature and precipitation data from meteorological stations in the vicinity of glaciers as well as discrete mass balance measurements for evaluation of precipitation, mass balance and melting on glaciers and discharge to glacial rivers. The model will be applied to all the larger glaciers in Iceland within the framework of the Nordic project on Climate and Energy (http://www.os.is/ce).

Regarding operational predictions in ungauged basins, one of the corner-stones in the hydrological forecasting service at the Swedish Meteorological and Hydrological Institute (SMHI) is the synoptic water balance map (Bergström and Sundquist 1983; Häggström et al. 1996). The map consists of HBV models for each of the synoptic meteorological stations in Sweden. Regional model parameters, established by experience from existing model calibrations, are used. Sweden is divided into seven regions, according to dominating type of landscape, with classes ranging from alpine to predominantly agriculture. Predictions of discharge in ungauged basins are issued daily, together with presentations of snow conditions and soil moisture status.

Moreover, the SMHI provides runoff data for ungauged basins to the provincial authorities in Sweden since the middle of 1980's, in order to calculate transport of substances at sites where water quality measurements are available. This is done by using the HBV model with a common set of parameter for a specific region. The regional parameters are derived from simultaneous model calibration for all available monitoring sites (Johansson 1992). Attempts have been made to relate parameters to catchment characteristics (Johansson 1994), but uncertainty in meteorological input was found to be a bigger issue than model parameters. An additional problem is that there is not a unique set of parameter values, but several combinations may produce equally good results (Seibert 1997). Thus, it may not be meaningful to relate calibrated parameters directly to catchment characteristics. However, Xu (1999) obtained good results when the parameters of a monthly water balance model were calibrated on a group of catchments in Sweden and related to physical catchment indices, and finally transferred to independent catchments. One possible reason for the different conclusions may be the difference in possibilities for identifying parameters. The study by Xu (1999) investigated a simple model with only six parameters and a monthly time resolution, whereas Seibert (1997) applied the HBV model which has a greater number of parameters and operates on a daily time scale.

Large scale mapping of distributed water discharge from Sweden has been requested for the environmental sector (Fig. 3). Sweden is divided into 1000 subbasins, which are modelled by the HBV model with regional parameters and a national precipitation grid (described below). Time-series of modelled water discharge was compared to observations at 307 sites in Sweden: at 188 sites the volume error was less than 5%, 82 sites showed a volume error between 5 and 10%, while it was more than 10% at 37 sites. Hence, the model can be used for rather trustworthy distributed mapping of national water discharge. This national model has been applied for nutrient load calculations reported to HELCOM (Arheimer 2003) and in impact studies of hydrological consequences from climate change (Andréasson et al. 2004). For water quality issues, the HBV-N model (Arheimer and Brandt 1998) is frequently applied based on this model system, also for scenario estimates of mitigating measures to reduce eutrophication (Arheimer et al. 2004). More detailed databases on land use, crop distribution and nutrient emissions have been established for such purposes (Brandt and Ejhed 2003). As for the HBV model, the nitrogen model includes parameters that need calibration, which is made regionally and step-wise; first for groundwater, then rivers, and finally for lakes. The procedure should be accomplished by independent validation in monitoring sites that have not been involved in calibration. At present, this model concept for nutrient modelling is evaluated in blind-tests with hidden observations for several European catchments within the EuroHARP-project (http://www.euroharp.org).

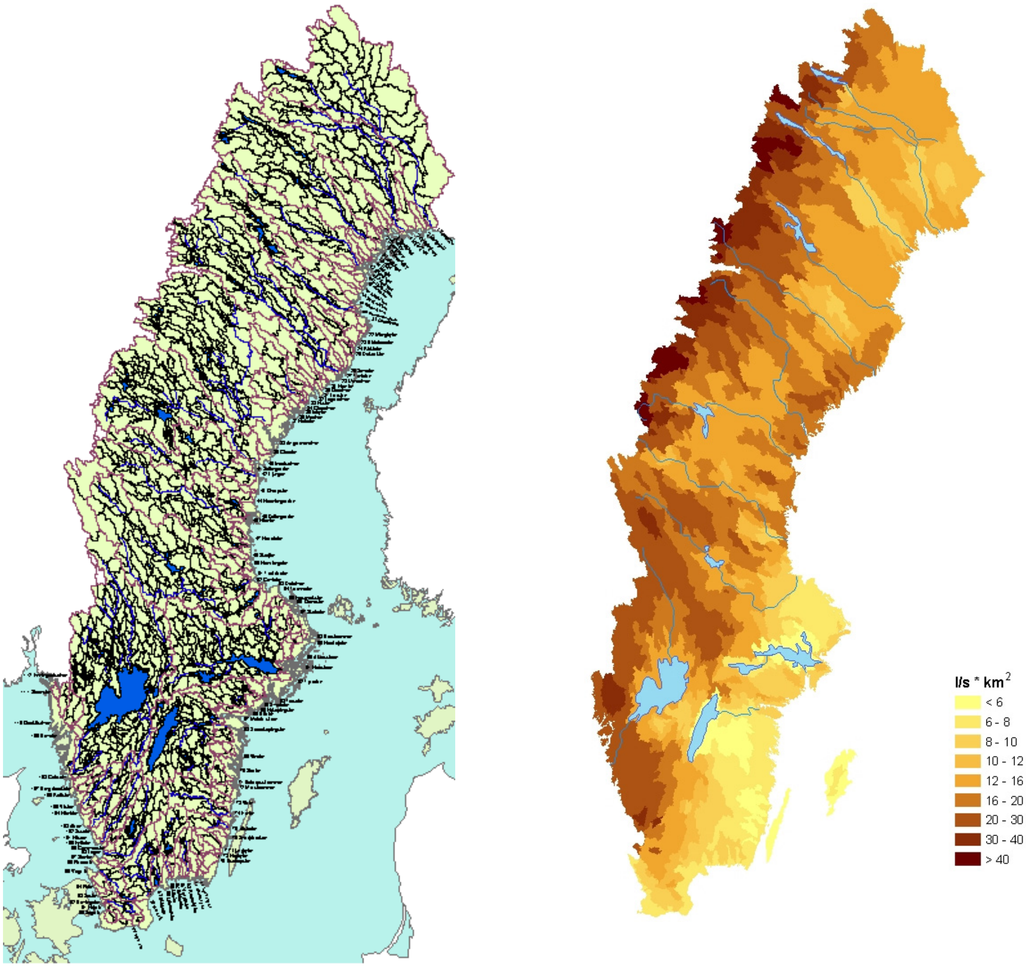


Figure 3. Division of Sweden into 1000 coupled subbasins (to the left), for which predictions are made regularly of water discharge (to the right) and nutrient transport (modified from Brandt and Ejhed 2003).

Distributed models describe the hydrological variability that occurs at a range of spatial scales by subdividing catchments into computational elements. Processes with a length scale larger then the element size are represented explicitly by element to element variations. The variability within the computational elements may be neglected or quantified by distribution functions. The Norwegian Water Resources and Energy Directorate (NVE) simulated runoff from the entire land surface of Norway with a distributed version of the HBV model using 1 km^2 grid cells and daily time step (Beldring et al. 2003). The model was sensitive to changes in small scale properties of the land surface and the climatic input data through explicit representation of differences between model elements, and by implicit consideration of sub-grid variations in moisture status. A geographically transferable set of model parameters was determined by a multi-criteria calibration strategy, which simultaneously minimized the residuals between model simulated and observed runoff from catchments located in areas with different runoff regimes and landscape characteristics. Model discretization units with identical landscape classification were assigned similar parameter values. Basins covering a large range of variations in runoff conditions for several landscape types and seasons where different runoff generating mechanisms dominated were considered. Model performance was mostly satisfactory for the 141 catchments used for calibration, as well as for the 46 independent catchments used for validation. Fig. 4 (top) shows observed and simulated snow water equivalent at a snow pillow located within a basin which was not used for calibration. For some years the snow pillow was not in operation at the beginning of the winter. Fig. 4 (bottom) shows observed and simulated runoff from the same catchment. The agreement was good, with a Nash-Sutcliffe efficiency of 0.76.

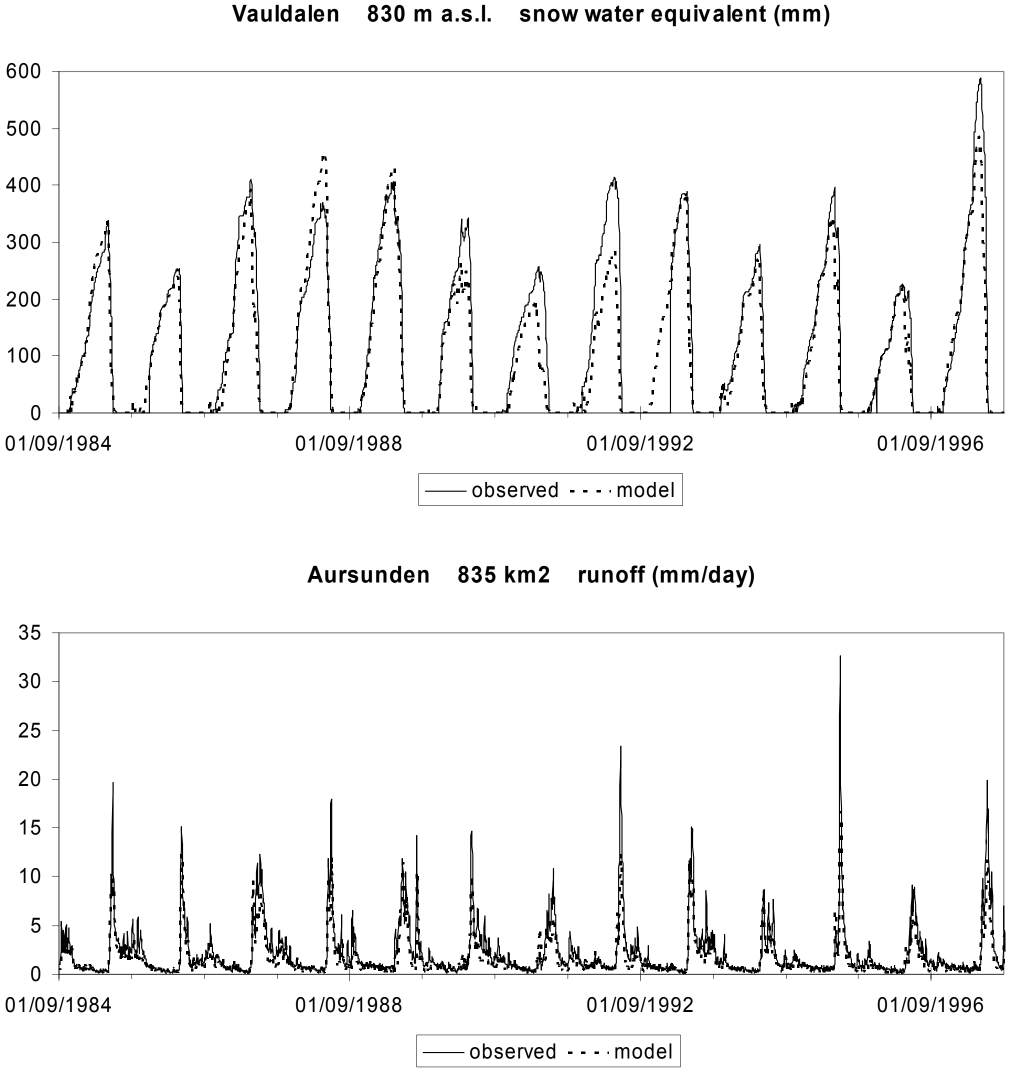


Figure 4. *Top:* Observed and simulated daily snow water equivalent at Vauldalen (830 m a.s.l.) in the Aursunden catchment, Norway for the period 1 September 1984 to 31 August 1997. *Bottom:* observed and simulated daily runoff from the Aursunden catchment for the same period (modified from Beldring et al. 2003).

Kitterød and Finsterle (2004) modelled unsaturated flow in a marine delta at Gardermoen, Norway using a finite-difference solution to Richards' equation. The model domain was discretized in regular elements of dimensions 0.5 m · 0.5 m · 0.05 m (x, y and z-directions). The parameters were based on soil samples and included as a priori information. Model performance was evaluated by comparing breakthrough curves from tracer tests with simulated breakthrough curves. Skaugen (1999) and Engeset et al. (2004) estimated spatially distributed snow water equivalent using meteorological data and models of snow accumulation, snow re-distribution and snow melt. Both studies obtained reasonable results compared to data from snow pillows.

Extensive data sets at multiple space and time scales and approaches to dealing with multi-scale variability were central elements of the Northern Hemisphere Climate Processes Land Surface Experiment (NOPEX) (Halldin et al. 1999). Improved models with the aim of coupling hydrological process descriptions and conservation equations with the spatial patterns of hydrological variables significant for runoff formation and evapotranspiration were considered. NOPEX is an example of a research programme in highly instrumented and extensively gauged basins with the aim of improving hydrological models, which is one of the objectives of the IAHS PUB science plan (Sivapalan et al. 2003a). Two model studies applied global parameter sets conditioned on catchment characteristics, but without site-specific calibration: Motovilov et al. (1999) used the ECOMAG model for predicting runoff, groundwater levels and soil moisture content at the meso-scale, while Beldring et al. (2000) simulated the same variables with a model based on kinematic wave approximations to saturated subsurface and overland flows in two small catchments. The landscape discretization in these studies was based on results from Beldring et al. (1999), who showed that an appropriate size of the computational elements of a distributed model is determined by the spatial scale where the variability of the state variables that govern runoff and evapotranspiration fluxes has a minimum. Both studies applied multi-objective calibration and validation strategies, where runoff, depth to the groundwater table and soil moisture content were considered. A critical point was preservation of scaling properties from fundamental hydrological response units to the basin scale.

4 Input data and state variables

A classical problem in hydrology is estimating the spatial distribution of meteorological data. Accordingly, a lot of efforts have been spent on improved model input, especially precipitation interpolation. Gottschalk and Jutman (1983) compared a geostatistical approach to Thiessen polygons and concluded that the statistical method had the smallest interpolation error. This method is similar to optimal interpolation, which is commonly used by meteorologists for Sweden (Häggmark et al. 2000) and the Baltic sea drainage basin (Omstedt et al. 1997). For hydrological purposes, this methodology has been developed recently to obtain a typical daily precipitation pattern derived from statistical analysis of wind distribution and topographic variables (Johansson 2002). The method has been applied for interpolation of daily point precipitation to a gridded database (4x4 km^2) covering the period 1961-2003 for Sweden, and generally improves water flow predictions compared to manual interpolation. For shorter time-steps, precipitation estimates by radar may be an alternative (Michelson et al. 2000). The temporal and areal inhomogeneities found in the radar data are further analysed in several on-going research projects to improve the applicability for, e.g., hydrological forecasting.

Spatial interpolation of precipitation in Norway in order to investigate the effects of station network density and different interpolation strategies on areal precipitation was performed by Tveito and Førland (1998). Udnæs (2001) applied precipitation simulated by the numerical weather forecast model HIRLAM for streamflow forecasts with the HBV model, while Skaugen (2002) presented a procedure for disaggregating grid cell precipitation from the atmospheric model HIRLAM. This approach combined interpolation of pixels within grid cells based on values in the nodal points, determination of the intermittency of the precipitation field and use of the exponential distribution for the fraction of the grid cell receiving precipitation.

Meteorological stations are generally sparsely distributed in Iceland, most are located close to the coast while few are up in the highland. Precipitation gradients have usually been estimated from observed discharge data, but recent development allows hydrological modelling without calibrating these gradients. Reducing the number of calibrated parameters is an advantage when modelling ungauged watersheds. A MM5 numerical simulation model has been used to map precipitation in Iceland and the results have been compared to glacier mass balance data and a statistical model based on observations and a number of topographical and geographical predictors (Rögnvaldsson et al. 2004). The model supplies precipitation and other meteorological parameters on an 8x8 km^2 grid with a time resolution of 6 hours. The output from this model will be used to drive hydrological models.

Remote sensing methods which have been properly calibrated and validated with ground truth data provide information on the spatial distribution of state variables and land cover. These technologies have been used to map and quantify the snow store in the Nordic countries in order to improve predictions of snowmelt in ungauged basins. The main satellite sensor (NOAA-AVHRR) has been used for updating the snow store in the HBV model (Häggström 1994). In addition, the applicability of ERS-SAR for snow cover analysis has been demonstrated very useful for cloudy days. However, recent results indicate that further testing is required before SAR can be used with confidence (Caves et al. 1999). Several studies have shown that the snow water equivalent can be observed by, e.g., airborne impulse radar (Brandt and Bergström 1994; Lundberg et al. 2000), but only for limited areas and periods. In the EU-project Hydalp it was shown that it was possible to convert the satellite information by means of a snow model for improved runoff forecasts in Sweden (Johansson et al. 2001). Marchand et al. (2003) compared snow depth measurements from ground-based and airborne georadar in Norway. The agreement was generally good, although the larger footprint of the airborne radar led to problems with detecting small, snow-free areas. On average, the airborne measurements indicated shallower snow depth than the ground-based measurements.

An issue of great practical and theoretical interest is objective methods for updating of spatially distributed models, based on optimal use of information from different sources. This can be accomplished through a process known as data assimilation. This is a technique that is most closely associated with atmospheric data analysis where it is used to generate a consistent four-dimensional picture of the state of the atmosphere taking advantage of the great variety of atmospheric observations. The purpose of data assimilation is to provide the proper initial conditions for the forecast models. Although these techniques are used in weather forecasting, the authors of this work are not aware of any attempts to integrate meteorological and hydrological models using 4-dimensional data assimilation algorithms in the Nordic countries.

5 Conclusions

Due to the need for mapping and management of water resources, the national hydrological services in the Nordic countries have been required to provide information about hydrological processes in ungauged catchments, sometimes under conditions of changes in land use and climate. The hydrological systems in the Nordic countries are usually closed over a river basin, which gives a valuable control on the water balance. As a result, the approaches to PUB which have been presented in this work capture the main features of the spatial patterns of hydrological processes. At least two approaches to PUB have been applied with good results in the Nordic countries: (1) Systematic approaches to transfer of information from gauged catchments guided by observed data and catchment characteristics, including characterization of space-time variability; (2) Use of conceptual or physical/chemical models without local calibration, but with a priori information relating model parameters to the characteristics of the systems under consideration. In both cases the quality of the data defining or driving the model may be just as important as the model characteristics.

Characterization of state variables and meteorological input data using remote sensing technologies or spatial interpolation methods are frequently applied in the Nordic countries. These methods are unable to foresee future events, but they provide information on the initial factors that are required for performing predictions or forecasts. The quality of data is important for the strategies which are used for characterizing state variables and input data, as well as for the methods used to perform predictions or forecasts. An algorithm for distributing observations in space or a simulation model cannot replace observational data, only complement them. In particular, it is observational data that allows research workers to accept or reject hypotheses about hydrological processes (Gottschalk and Askew 1987).

According to the definitions of PUB, predictions or forecasts must be performed using all data sets other than past observations of the hydrological response to be predicted. However, use of independent observations of the variable to be estimated should be performed for validation of methods. One of the challenges of PUB is that our understanding of natural variability must be sufficient to also make predictions under changed conditions, including human-induced climate change and land use changes. We are not only dealing with extrapolation in time and space, but also with extrapolation to future changed circumstances. Methods based on the assumptions of stationarity and equilibrium are therefore no longer sufficient. The hydrological prediction or forecast system, i.e. the model, its parameters and the appropriate meteorological input data, should therefore perform well under conditions of geographical transposability and non-stationarity as defined by Klemeš (1986).

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