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IMPROVEMENT OF THE NATIONAL FLOOD EARLY WARNING SYSTEM IN NORWAY – FLOOD LEVEL WARNINGS AND UNCERTAINTIES

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This work describes the methods and procedures applied to improve the national flood warning system in Norway by including water level forecasts at non-gauged but important locations and information on the corresponding uncertainty. In this approach, only a subset of model variables (inputs) and parameters are treated as uncertain. It is found that visualization of the forecasts is challenging, and therefore a number of experimental solutions are discussed.

BACKGROUND

The national flood early warning service (FEWS) in Norway is organized by the Norwegian Water Resources Directorate (NVE). The system is being constantly developed reflecting to expectations from the public, the parent authority and advances in technology.

The forecasts issued by the FEWS currently contain region specific information on awareness level on a four-level scale. The awareness level system follows international practices[1], and is considered easier to communicate than flood levels and return intervals. In special cases, information on water levels is also included, but this information is occasional, not standardized and the forecast values are not published in “absolute” terms.

Water levels on the one hand are commonly measured and used as reference to describe flood magnitudes and are easily communicated to the public. The FEWS on the other hand rather operates with and communicates runoff (discharge) values for reasons related to methodology and modelling technique. There is therefore an obvious need to forecasting water levels but it is at the same time challenging and uncertain at non-gauged locations. Uncertainties are related to lacking reference levels for calibration and unclear functional relations due to estimated data [2].

Currently uncertainty is only considered until reaching the calculation of runoff forecasts in the forecasting procedure of the FEWS. This article describes the extension of forecasts to include flood (water) levels as well as information about related uncertainties in their calculation.

The Flood Early Warning Services in Norway

The HBV model

For precipitation-runoff modelling, NVE uses the conceptual HBV model for simulation of runoff processes in selected indicator catchments as part of the FEWS.

The model is semi distributed with option for a number of elevation zones describing the snow distribution with elevation in each catchment. The model further consists of a soil moisture zone, an upper zone describing the quick overland runoff and a lower zone describing the groundwater runoff. The model uses precipitation and temperature data as input. The model is principally calibrated against observed discharge at the outlet of the actual catchment (at gauging stations). For further details about the HBV model see [3]. Specifications concerning the variant of the HBV used by the FEWS is described in [4]

Uncertainty in the runoff forecasts

The Norwegian Meteorological Institute (MET) provides the FEWS with forecasts of temperature and precipitation and related uncertainty. The MET data and historic recorded runoff are fed to the rainfall - runoff models to calculate forecasts at these stations. The FEWS has been developing a large number of rainfall-runoff models representing the country in terms of hydrological diversity, associated with gauging stations with real-time access to measured data. Uncertainties related to the model mechanism- and to the precipitation and temperature data are also considered [5, 6]. In practice, the uncertainty forecasts are corrected daily to match the last observations.

The Flood Inundation Maps project

Parallel to the FEWS development, a large number of flood inundation maps (FIMs) were developed as one of the mitigation measures to promote improved land use planning and emergency preparedness related to future floods. These are based on a combination of digital elevation models (DEMs), surveyed cross-section data and mostly one- or sometimes two-dimensional hydraulic models.

The FIMs are developed for various statistical return periods of floods, based on historic data from the aforementioned gauging stations. These hydraulic models are therefore mostly steady state models, with a few exceptions, where the length of the river reach in focus or the speed of the flood wave suggest dynamic (unsteady) modelling. The models are calibrated to water level data collected at relatively high discharges. Historic events causing floods (like ice development, sediment deposition or scour, etc.), are also considered, in addition to the statistical analysis. Uncertainty in the FIMs is not analysed in detail, but the expected inaccuracies in DEMs are estimated as ± 0.3 m. Uncertainty in flood level estimations are therefore expected to be somewhat higher. The FIMs are presented as hardcopies and digital maps, longitudinal profiles and textual descriptions [7].

The locations for FIMs are selected based on public interest and surveys of risks related to population density, economical production, and other aspects. The hydraulic models used to calculate inundated areas and flow levels are developed in HEC-RAS [8] or Mike 11 [9] and remain as high quality by-products, which are therefore reused and further developed in the present project. Figure 1 shows an overview of the dataflow and processes as well as where uncertainties are considered today.

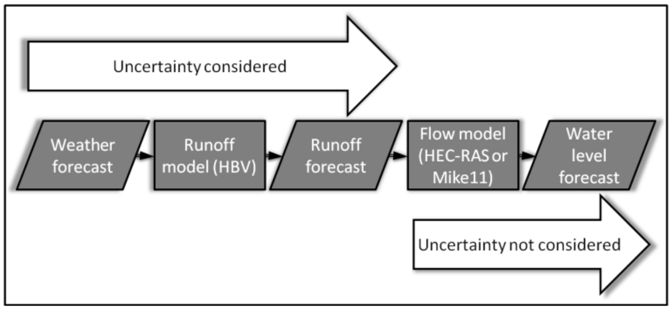

Figure 1: Flow of data and processes from meteorological to water level forecasts and calculations of related uncertainty as performed today

Uncertainty analysis in water level forecasts

Calculation and presentation of uncertainties concerning flood levels are considered mandatory in the relevant literature (see for example [10, 11]). It is however also important to consider credibility and relative importance of the forecast alternatives of the starting data, which are to be used as input to an analysis. Credibility can be evaluated by means of uncertainties linked to the data. Large spreading of uncertainty indicates the low credibility and warns the analyst of possibly useless results. Best in such cases is to admit the lack of usual level of certainty and only consider and communicate parts of the analysis which can still be trusted [12].

Uncertainty studies [13, 14] applied the generalised likelihood uncertainty estimation (GLUE) methodology to evaluate uncertainties in results of hydraulic models developed in HEC-RAS. Even though only a selected parameter and variable were considered, the findings show the complexity and sensitivity to different sets of uncertain data. It is pointed out that the structure of the hydraulic model and its inner elements can have large impact on the uncertainty ranges of the results.

Uncertainty can be considered by accumulating effects of various types and sources of errors in model parameters and variables on model results, in the present case on forecasted water levels. At the same time, it is challenging to perform a global analysis of all possible factors having an impact on the calculation, due to limited or no access to verification data and other reasons. It is also obvious that out of the large number of factors to be possibly considered, only a few will have considerable impact on the results. Therefore it is advisable to restrict uncertainty analysis to a limited number of selected factors [15].

There exist various methods to eliminate a subset of uncertain factors from the analysis, both objective and subjective for different applications. These “protocols” may also be combined as long as each case is considered unique and no “general” solutions are selected without criticism. The combination should be unique and based on careful study of relevant literature, the actual problem and model structure in each case [10].

In addition to calculating the numerical uncertainty from all possible sources, decision-making must also consider risks related to the alternatives. Missing doing so, the usefulness of the analysis would become questionable. This is to underline that uncertainty analysis alone does not qualify as a decision support tool [11].

METHODS AND MODELS

The runoff forecasts used as input for the water level forecasts are provided as time series with daily time-steps. This would normally suggest a dynamic (unsteady) solution in cases where the speed of the flood wave is considerably longer than one day. Most hydraulic models (to be reused) are however developed for steady-state cases, which require separate simulation of the forecasted days, independently from each other. In the few cases where unsteady models are available, they are kept in that form.

The previously cited sources suggest various solutions for the uncertainty analysis. A version of the Monte Carlo method was selected in combination with a strategic sampling solution, Latin hypercube sampling (LHS [10]). Therefore, key uncertain parameters of the hydraulic models had to be identified, as well as their statistical distribution, their statistical independence and natural limits. From the practical point of view, a tool (uncertainty analysis tool, UAT) was also necessary to be able to generate new variations of the original hydraulic models with the given parameters, run them and summarize their results, because the original hydraulic models were commercial products from external sources.

Standardized hydraulic models

The hydraulic models used in this study are developed either in HEC-RAS (steady models) [8] or in Mike 11 (unsteady models) [9]. HEC-RAS model components are ASCII text-files and so their content can be manipulated by reverse engineering. Mike 11 stores some model files in ASCII, but others in binary format. To access and manipulate the contents of these latter types, special programming tools are necessary from the software producer.

The hydraulic models were developed following different standards. To be able to use the UAT on them, they had to be standardized. Examples of differences spread from number of digits in geometry data, through the distribution of hydraulic roughness in the cross sections or flow depth-roughness functions, as well as types of boundary conditions.

Monte Carlo simulation with Latin Hypercube sampling (LHS)

The fact that hydraulic simulation models require specific software and simulation time to perform even such a simplified simulation as in these cases is non- negligible. Real time flood forecasting, which is the ultimate application field of the study is time-critical and therefore minimizing simulation times are important. The modelling tools used and practical concerns suggested a maximum of 98 new variations of the hydraulic models, but the LHS sampling is expected to compensate for the small sample size, while keeping the sampling accuracy [11, 16, 17].

The FEWS are an on-going live operation, where pragmatic solutions and small development steps are preferred in order to maintain operation security and readiness. This requires introducing only a limited number of changes to existing systems. Development has to be transparent because it is followed by a large number of users and experts with various background and experience. Therefore, a non-global uncertainty analysis was suggested with the possibility to extend the number of uncertain variables later on if necessary.

Screening for non-global uncertainty analysis

Research showed that discharge, channel width, depth (accuracy of rating-curves), velocity and slope are the most relevant factors to consider in similar cases. Since slope is functionally related to others and flow velocity is not given as input or specified as parameter in the hydraulic modelling tool used in the study, they can be neglected [18].

The selected parameters are main channel width, flow depth and hydraulic roughness. Uncertainty in model variables is considered at the upper and lower boundaries. For logical reasons related to distributing the uncertain variants of the uncertain parameters in the models, these are grouped as “model variables” (discharge and downstream water level, abbreviated as VA) and “model parameters” (hydraulic roughness, main channel width and flow depth, abbreviated as PA).

In order to be able to perform the analysis, the empirical distribution and reasonable limits need to be given for all VA and PA. Related uncertainty is provided with the runoff forecasts, so its empirical distribution and spreading is given for the present analysis. All other VA and PA are assumed to be normally distributed. The user needs to specify bounds for the length-type parameters, while bounds for the roughness factors are taken from literature [19].

Distribution of uncertain values among model parameters and variables

In this study, the focus is on uncertainty of hydraulic models, where river cross sections are building blocks of the whole. The selected VA are linked one-to-one to the whole model, so one set of (2 times) 98 model variants are sufficient. However, the PA usually vary within a hydraulic model (from cross section to cross section, in a case of a calibrated hydraulic model), which require a different method for distributing the PA. In this case, 98 values of PA are generated for each cross section and one value is picked from this generated set while reducing the number of samples stepwise for each particular realisation of the uncertain model. Statistical independence is assumed between VA and PA, so two sets of analyses are required for each model.

UA tool realization

A Microsoft .NET Framework 4.5 C# [20] code is used to extract and restructure data from model files, to gather forecast data and to make this available to R [21]. A graphical user interface was developed to collect parameters given by the user. The resampled VA and PA produced by R are used to prepare new model versions by the C# code.

Both modelling tools (HEC-RAS and Mike 11) allow running several models one after the other and their results to be jointly analysed. R is used here again to generate figures of the results [22].

RESULTS

Below is a case where historic runoff forecast and measured sea water level data are used to reproduce simulated uncertainty of water levels at a gauging station called 109.42 Elverhøy Bridge on River Driva, Norway. Due to the limited extents of this article, only the effects of uncertainty in runoff forecasts and sea levels are shown, and the effect of uncertain model parameters are not presented here.

The runoff forecasts (upper boundary criteria) are based on measured data from the same gauging station and the hydraulic model is calibrated to a higher flood than what is modelled in the present case. The modelled reach is influenced by tidal variations, considered in the lower boundary criterion. Uncertainty is considered by using the mean measured daily sea levels with maximum daily measured deviation as bounds and normal distribution.

Figure 2 shows estimated uncertainty of water levels together with (post-event) measured data. The daily corrections of uncertainty forecasts (to match the last observations, see above) were not recorded, therefore the medians of the first forecasted values were adjusted to match the last observation. Consequently, all following forecasted days inherited this adjustment. The dashed and dotted lines on the left and right side of the figure show the measured data, whereas box-plots show the 5%, 25%, 50%, 75% and 95% exceedance levels and outliers from simulations. Forecasts prepared on five consecutive days are shown starting from the bottom and ending on the top. Each forecast includes 9 days, starting on the day of its preparation. These are ordered in columns on the plots. The flood-peak was registered on 19.05.2013, where the measured data reaches their maximum.

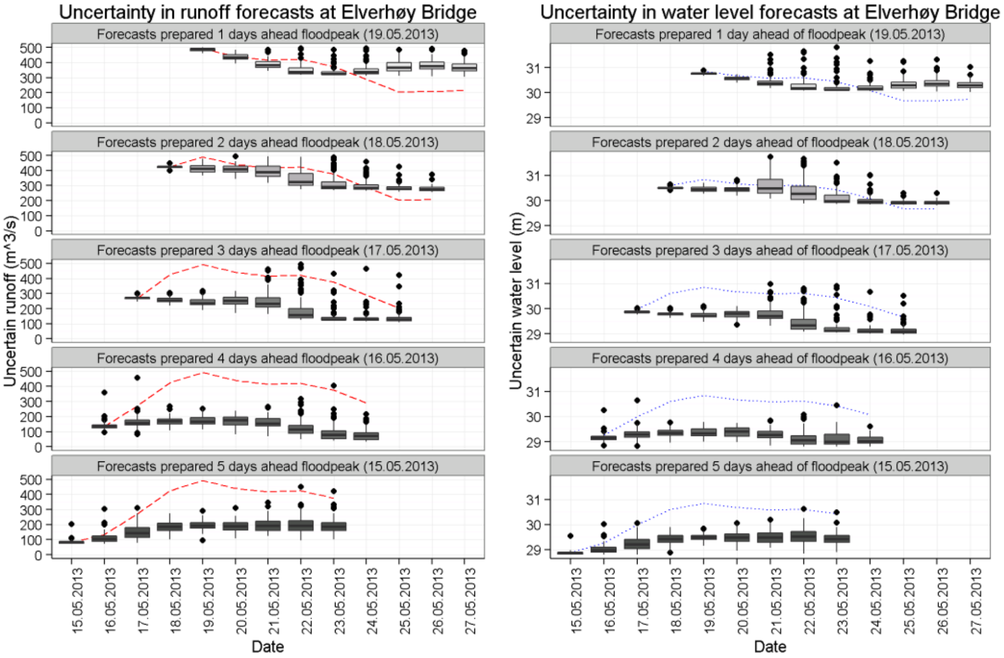

Figure 2: Estimated (boxplots: 5%, 25%, 50%, 75% and 95% exceedance levels and outliers) and measured (dashed or dotted lines) uncertain runoff (left) and water level (right) at Elverhøy bridge

DISCUSSION

The results show that at this particular location the uncertainty in water level forecasts follow the trend and spreading of those received from the runoff forecasts. The ranges however between 25% and 75% exceedance limits seem practically more useful in the case of water levels compared to runoff. The poor quality of these particular runoff forecasts clearly causes a similar type of error in the water levels as well. A study covering a much longer period (several flood peaks) showed good quality at this station and therefore it can be stated that the selection of this particular flood was simply atypical considering forecast quality. Water level seems to have a bias of approximately 0.12 m, which can be caused by calibration error in the hydraulic model or a difference between references in the observations and model elevations.

CONCLUSIONS

The study presented the main steps to develop a practice-oriented uncertainty analysis system for 1D hydraulic models based on known or estimated uncertain inputs and model parameters. The results show that such analysis is greatly dependent on the quality of underlying data. Operational use in early warning services is concluded possible, but with common precautions, meaning acceptance and recognition of the limitations and variations of forecast quality.

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