Natural Hazards (2005) 36: 237–256

An Integrated Approach for Realtime Floodmap Forecasting on the Belgian Meuse River

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(Received: 17 October 2003; accepted: 30 June 2004)

Abstract. The last important floods of the Meuse river have shown the need to design powerful and real-time forecasting tools. With the support of CESAME and the department of Civil and Environmental Engineering at UCL, the Service of Hydrologic Studies (SETHY) of the Walloon Ministry of Equipment and Transport developed two models: Hydromax and Hydroaxe. These two complementary and user-friendly applications work with the data provided by the measurement network of SETHY (raingauges, water levels, discharge measurements, weir-gate positions). Hydromax produces local river flow forecasting for the main natural tributaries of the Meuse. These predictions are used by Hydroaxe to compute discharge propagation and water levels all along the Meuse. In Hydromax, the predictions are produced by a grey box model which involves two main parts. A nonlinear production function computes the effective rainfall from the mean areal rainfall. This part is based on a conceptual approach, the river basin being modelled as a reservoir. In the second part, a linear ARX (AutoRegressive model with eXtra input) transfer function (black box), describes the superficial runoff of the effective rainfall towards the watershed outlet. This transfer function is used to compute short term river flow predictions. Hydroaxe uses a Preissmann finite difference scheme to solve the Saint-Venant equations of shallow-water, completed with the Exchange Discharge Model describing the momentum exchanges between the main channel and the floodplains. The optimisation of the computation time requires a one-dimensional approach, based on a dense (1 point/m^2) and accurate (15 cm in x, y, z) topography provided by SETHY and carried out through an original combination of technologies: swath bathymetry and airborne laser (Lidar). With the help of a GIS (Geographic Information System) and the DTM (Digital Terrain Model), the water levels calculated by Hydroaxe are transformed in flooded areas, fitted for an easy and fast overview of the extent of the flood event.

Key words: Meuse river, flood, forecasting, real-time, GIS, DTM

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1. Introduction

The early warning of extreme hydrological situations, all over the Meuse river basin, is one of the main missions of the Service of Hydrologic Studies (SETHY) of the Walloon Ministry of Equipment and Transport. The Meuse is a navigable river, which flows through France, Belgium and the Netherlands. Its catchment has an area of 12,220 km^2 in Wallonia (southern Belgium), i.e. 73.3% of the Walloon territory (see Figure 1). The tributaries of the Meuse are notable for their very varied characteristics, with very high flows in winter and extremely low waters in summer.

The big floods in 1993 and 1995 have shown the need to perform real-time forecasting of water levels and flooded areas. With the technical support of CESAME and the department of Civil and Environmental Engineering of UCL, SETHY has started the development of two applications: Hydromax (Moens and Bastin, 1995) and Hydroaxe (Scherer, 1999; Adriaensen, 2001; Dal Cin, 2002).

Since 1995, Hydromax produces real-time local river flow forecasting for the main natural tributaries of the Meuse river. For 6 years, Hydromax can also forecast high river flow at three stations on the Meuse river. Several predictions of Hydromax are used by Hydroaxe to compute discharge propagation and water levels all along the Meuse river. Hydroaxe is based on 1D shallow water equations according with the river profiles and including the effect of the floodplains. Hydroaxe is currently operational on the Walloon Meuse. As Hydromax, Hydroaxe was developed to meet the

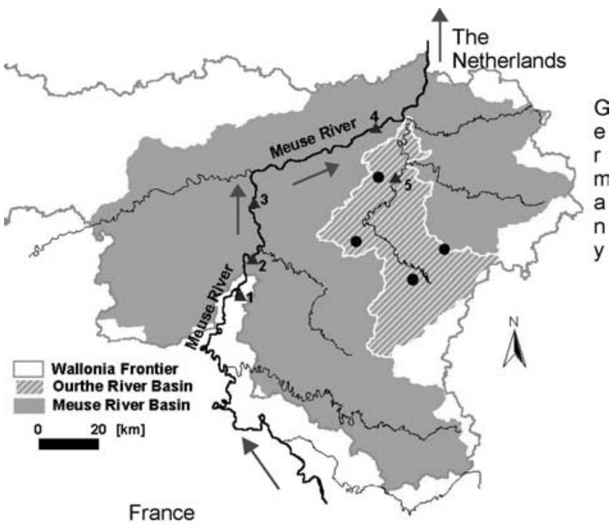

Figure 1. The Walloon Meuse river basin and its main tributaries. (Locations: 1 = Chooz, 2 = Waulsort, 3 = Lustin, 4 = Ivoz, 5 = Tabreux. The dots are the raingauges used by Hydromax for the forecasting of Tabreux.)

requirements of an efficient real-time forecasting. These two applications are connected in real-time to the measurement network of SETHY.

Thanks to a dense and accurate Digital Terrain Model (DTM) obtained through laser scanning and swath bathymetry, the water levels produced by Hydroaxe are then used by a Geographic Information System (GIS) to draw flood maps.

The flood maps produced at the crisis centre of SETHY can be used as a support for the real-time management of an incoming flood, as well as a tool to develop a long-term water management policy.

The present paper will first give a short description of the major functions of SETHY. The paper will then focus on the three parts of the forecasting tool: Hydromax, Hydroaxe and the computation of flood maps with ArcView GIS.

2. The Service of Hydrologic Studies: SETHY

2.1. MISSIONS

SETHY has many missions about the water flows in the rivers and canals throughout the South of Belgium. Figure 2 shows its primary objectives and the interconnected means necessary to reach them.

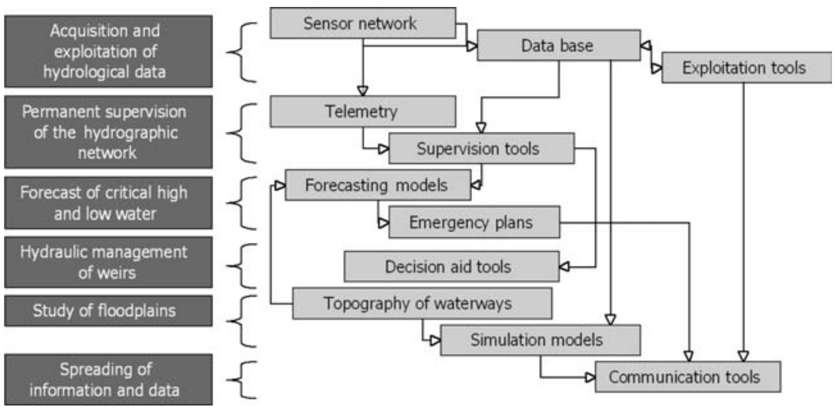

Figure 2. Missions and means of SETHY.

Many hydraulic structures are located in the Walloon hydrographic network: dams, weirs, reservoirs, locks, hydropower plants, pumped storage plants. They have numerous and sometimes conflicting interests: navigation, drinking water reserve, flooding mitigation, tourism, power production. SETHY has permanent contacts with the public and private organisations in charge of these structures, in order to guarantee a comprehensive and coherent management of the water resource.

2.2. MEASUREMENT NETWORK AND PREDICTION MODELS

The measurement network is the cornerstone of applied hydrology. A dense, complete, coherent and integrated network, all over the Walloon region was developed and managed for many years. Today, more than 230 hydrologic stations are working on this territory of approximately 18,000 km^2. The real-time network records accurately the rainfall, the water levels and the discharge of rivers and lakes, together with the positions of weirs across waterways. SETHY's network incorporates state of the art techniques: weather radar, ultrasonic flowmeters, laser sensors, etc. All measurements are stored directly in a huge database with specific management tools integrated: quality control, supervision, exploitation, internet dissemination, warnings, etc.

One of the main missions of SETHY is the early warning for extreme hydrological situations. For the prediction of discharge, Hydromax (see Section 3) was developed and, on another hand, Hydroaxe (see Section 4) for the water levels and flooded areas. These two relevant applications for real-time flood forecasting are handled as shown in Figure 3.

2.3. INVESTIGATION OF FLOODPLAIN AREAS

The knowledge of floodplains is a complex task but definitely necessary to draw flood-map forecasting (see Section 5). SETHY organises aerial photograph surveys during flooding and field surveys after flooding. However these actions only show the extension of flooded zones and are not sufficient to compute occurrence or risk probabilities. Hydraulic models must be used, but in many cases the topography of floodplains areas and the bathymetry of rivers are not known with adequate accuracy. Conventional techniques (land survey, photogrammetry, remote sensing) are either too slow, or too expensive, or too inaccurate. In order to obtain the best information for the hydraulic models, SETHY has set an ambitious objective at the end of the nineties: the creation of a DTM with very stringent criteria (density of 1 measured point per m^2 and an accuracy of 15 cm in x, y, z). The 15 cm in altitude is required in Belgium due to the topography of the floodplain. A water-level small difference could highly affect the inundation extension. To achieve these objectives, SETHY has carried out surveys using an innovative combination of state of the art techniques: swath bathymetry and airborne laser (also known as Lidar). The surveys have been conducted on 450 km of waterways and 1500 km of smaller rivers.

2.3.1. *River Bathymetry*

For the bathymetric survey of waterways, SETHY implemented swath bathymetry (see Figure 4). This technique is frequently used offshore. But on

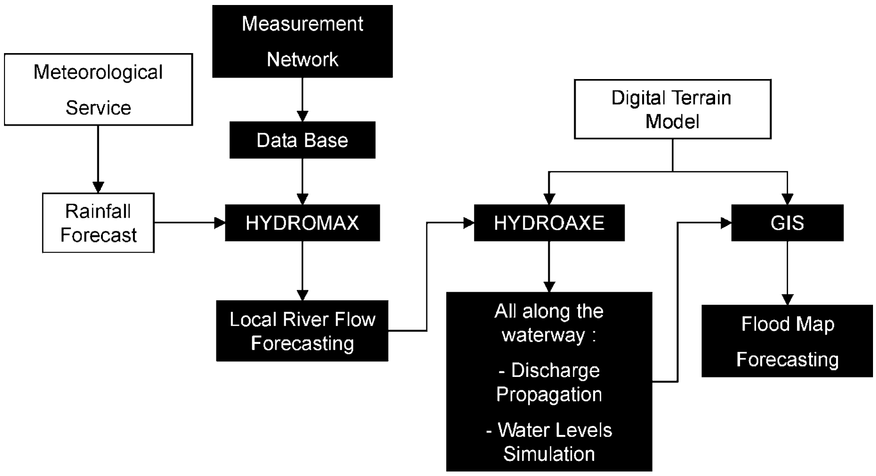

Figure 3. From the measurement network to the real-time flood forecasting.

rivers, specific problems had to be taken into account: shallow depth, obstacles (bridges, trees along the banks, narrow valleys, meanders) for DGPS (Differential Global Positioning System). Swath bathymetry records depth profiles across tracks. Acquisition rates of several profiles per second are achieved. Motion sensors measure the roll, pitch and heave. A gyro gives the heading and RTK (Real-Time Kinematic) DGPS positioning gives a centimetre accuracy. The GPS positioning is combined with inertial navigation or with land survey in areas where obstacles preclude a good reception of GPS signals. The unprocessed profiles are displayed onboard.

The DTM was originally built for hydraulic modelling, but it is also very useful for navigation and dredging operations. The technique is very fast and generates no obstacles for the navigation since the measurements are realised along length tracks.

2.3.2. *Survey of the Valleys*

For the survey of valleys and floodplains (see Figure 5), SETHY implemented airborne laser (LIDAR) which provides a high frequency scanning of the ground (more than five point by square meters). The aircraft is positioned by DGPS and an inertial system records the heading and the movements. In addition to the high acquisition rate and the fairly low cost of this technique, the laser gives a possibility to record several echoes. Frequently, the first and the last echo are recorded (see Figure 5).

This is a major benefit of the technique since it gives a possibility to generate an “envelope” DTM and a “soil” DTM which correspond to the top and the base of the vegetation respectively. The last one will be used in the hydraulic models. No other teledetection system offers this result.

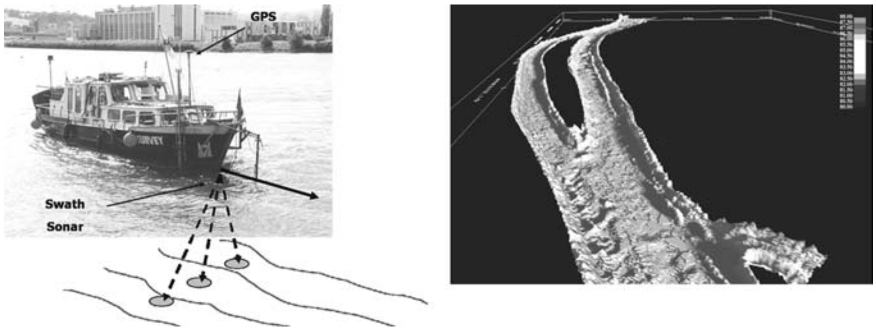

Figure 4. Bathymetric survey with swath sonar.

2.3.3. *Combination of DTM*

The river DTM created by sonar (see Section 2.3.1) and the laser DTM (see Section 2.3.2) can be combined to describe exactly the actual topography of the river with 15 cm of accuracy. SETHY has now the best DTM for any kind of hydraulic models.

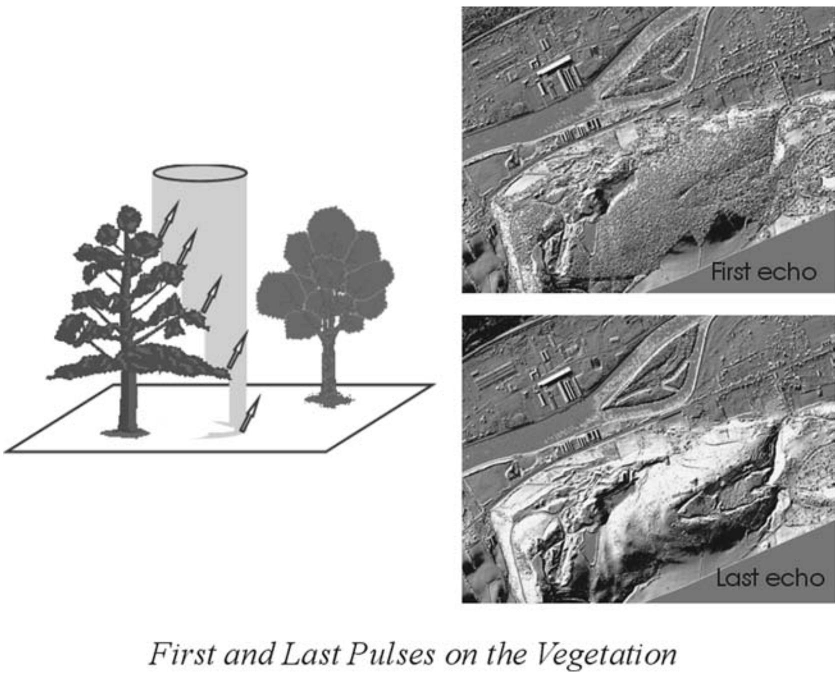

Figure 5. Survey of valleys and floodplains with an airborne laser (LIDAR).

3. Local River Flow Forecasting in Real-Time: HYDROMAX

3.1. INTRODUCTION

The purpose of this section is to give a general description of Hydromax and to demonstrate its performance with a typical example and statistical assessments. Hydromax provides in real-time local river flow forecasting, which is produced by a mathematical model. This model involves four parts.

(1) An optimal minimum variance interpolator which computes the mean areal rainfall on the watershed.
(2) A non-linear conceptual production function which describes the whole watershed as a single macroscopic reservoir. This function computes the effective rainfall from the mean areal rainfall.
(3) A linear ARX transfer function which describes the superficial runoff of the effective rainfall towards the watershed outlet and computes the short term river flow forecasting.
(4) A simulation model which produces long term river flow forecasts from meteorological data.

The identification of the model is quite data saving because only rainfall and river flow measurements are required while a detailed physical description of the basin is not needed. Hydromax has been developed to be user friendly and to fulfil the real-time forecasting requirements. It is successfully in routine operation since January 1995 for the main tributaries of the Meuse river.

Hydromax is directly connected to the hydrological data base of SETHY (see Figure 3). In real-time, about 100 stations of the measurements network scattered in the Meuse basin can be used by Hydromax. The data are collected with a basic time-step of 1 h ($\Delta t = 1$ h). Hourly rainfall and river flow measurements over a period of several years (including big floods) were thus available for the model development. Obviously, the basic time-step Δt must be much smaller than the concentration time of the considered river basins.

3.2. ESTIMATION OF THE MEAN AREAL RAINFALL

The input of the model is the mean areal rainfall over the considered watershed. The possible spatial heterogeneity of the rainfall is thus not taken into account here. The point rainfall depth is denoted $P(z)$ with $z = (x,\ y) \in \mathbb{R}^2$, the Cartesian coordinates. It is assumed to be a realisation of a two-dimensional random field with constant mean and linear variogram. The rainfall measurements are available at n measurement stations. The average areal rainfall PB over a catchment area $\Omega \in \mathbb{R}^2$ is then defined as:

$$\mathrm{PB} = \frac{1}{|\Omega|} \int_{\Omega} P(z)\mathrm{d}z \qquad (3.1)$$

As is well known, an optimal (linear, unbiased, minimum variance) estimation of PB can be computed from the set of rainfall observation $\{p_{i,i=1,\dots,n}\}$ as:

$$\mathrm{PB} = \sum_{i=1}^{n} \lambda_i P_i \tag{3.2}$$

with the λ_i solutions of the so-called "kriging" system (see Bastin *et al.*, 1984, for further details).

3.3. COMPUTATION OF THE EFFECTIVE RAINFALL WITH THE PRODUCTION FUNCTION

The role of the production function is to transform the mean areal rainfall PB into an effective rainfall PN which is supposed to reach the basin outlet as surface runoff. The model describes the balance of water volumes during time intervals Δt. During each time interval the amount of precipitated water is decomposed as follows:

$$\mathrm{PB}(t) = \mathrm{PN}(t) + E_1(t) + W(t) \tag{3.3}$$

with t the discrete time index. $E_1(t)$ represents the part of the rainfall PB(t) that directly evaporates during the current time interval. $W(t)$ represents the amount of water that will not participate in the runoff but will be stored in the basin under various forms (vegetation interception, superficial depressions, soil moisture). The storage of the water in the river basin is then represented by a linear reservoir with inflow $W(t)$ described by the difference equation:

$$S(t) = S(t-1) + W(t) - E_2(t) - I(t) \tag{3.4}$$

where $S(t)$ denotes the stock of water in the river basin, $I(t)$ is the amount of water drained by percolation and $E_2(t)$ is the part of stored water evapotranspirating during the current time interval. The percolation term $I(t)$ is represented by a linear function of the available water stock:

$$I(t) = \alpha(S(t-1) + W(t)) \tag{3.5}$$

with α a specific percolation parameter. The evapotranspiration terms $E_1(t)$ and $E_2(t)$ are computed as:

$$\begin{aligned} E_1(t) &= \min(\mathrm{PB}(t), \mathrm{ETP}(t)) \\ E_2(t) &= \max(0, \min(\mathrm{ETP}(t) - \mathrm{PB}(t), S(t-1) + W(t) - I(t))) \end{aligned} \tag{3.6}$$

where ETP(t) represents an estimate of the seasonal potential evapotranspiration for the considered basin. It is furthermore assumed that there is a physical upper limit $S_{\max}$ of the amount of stored water $S(t)$ in the river basin. The water storage $W(t)$ is then expressed as a function of $S(t)$ and PB(t) in order to:

- guarantee the condition $0 \leq S_{\max}$ for all t,
- verify the hydrological principle that the effective rainfall PN(t) increases with both rainfall intensity PB(t) and soil moisture $S(t)$. The following function satisfies these requirements:

$$W(t) = [S_{\max} - S(t-1)]\left[1 - \exp\left(-\beta \frac{\mathrm{PB}(t) - E_1(t)}{S_{\max} - S(t)}\right)\right] \tag{3.7}$$

with β a specific runoff coefficient.

The production function model then involves three parameters (α,β, $S_{\max}$) that have to be calibrated from experimental data for each considered river basin (Wéry, 1990).

3.4. COMPUTATION OF THE SHORT TERM RIVER FLOW FORECASTING WITH A LINEAR TRANSFER FUNCTION

At each time t, a forecasting $\hat{Q}(t+h)$ is computed for the future time instant $(t+h)$ (i.e., with a prediction horizon of h measurement time steps) as a linear combination of past river flow measurements and past effective rainfall values, with a linear regression model (ARX model) of the form (Ljung, 1999):

$$\hat{Q}(t+h) = \sum_{i=1}^{n} a_i Q(t-(i-1)h) + \sum_{j=1}^{m} b_j \mathrm{PN}(t-(j-1)h) \tag{3.8}$$

where $Q(t-(i-1)h)$ denotes the riverflow measurements at the past time instants $(t-(i-1)h)$ while PN$(t-(j-1)h)$ represents the effective rainfall cumulated over h successive time steps and computed with the production function.

For each river basin, the values of the prediction horizon h and the coefficients a_i, b_j are determined from experimental data. To get accurate forecasts, the prediction horizon h must obviously be smaller than the natural response time of the river basin. As a rule of thumb, it is selected between the one fifth and the one third of the peak time of the unit hydrograph. The dimensions n and m of the regression terms in the model are selected using classical statistical tools of system identification theory (correlogram of prediction errors, Bayesian Information Criterion, etc...) (Ljung, 1999) according to a parsimony principle. The parameters a_i and b_j are calibrated by linear regression.

3.5. COMPUTATION OF LONG TERM RIVER FLOW FORECASTS FROM METEOROLOGICAL DATA

The goal here is to compute river flow forecasts over prediction horizons that are significantly larger than the natural response time of the river basin. This obviously requires to anticipate the future mean rainfall $(\hat{\mathrm{PB}}(t+kh))$. In this case, it is provided by weather forecast and transformed by the production function (see Section 3.3) in future effective rainfall ($\hat{\text{PB}}(t + kh)$). The long-term river flow forecasts may be then computed by iterating the short-term prediction model (see Section 3.4, equation 3.8).

3.6. MODEL IDENTIFICATION PROCEDURE AND PARAMETER CALIBRATION

In order to identify a forecasting model for a given river basin, a set of rainfall – riverflow data must be available for a significant period of time involving floods as well as low water periods. The identification procedure can then be summarized in seven steps as follows:

(1) Computation of the mean areal rainfall PB(t) by kriging for each time step t.
(2) Computation of the unit hydrograph by spectral analysis of the data.
(3) Selection of the short term prediction horizon (see Section 3.4).
(4) Resampling of the data according to the selected short term prediction horizon.
(5) Using the data from flood periods only, identification of the dimensions n and m of the transfer function under the assumption that the effective rainfall PN is (almost) equal to the total rainfall PB.
(6) From the whole set of data, calibration of the parameters ($\alpha, \beta, S_{\max}$) by non-linear optimization and (a_i, b_j) by linear estimation, in order to minimize the mean square prediction error.
(7) Validation of the model with a new set of data that were not used in the previous steps.

3.7. AN EXAMPLE: THE FLOOD OF FEBRUARY 2002

In this section, the Hydromax performance is illustrated with a typical forecasting example in the Ourthe River basin (see Figure 1). The outlet of the river basin is located at Tabreux (1607 km^2) and four raingauges are available. Hourly rainfall-discharge data during 2 years (1992–1993) have been used to calibrate the model. The estimated model parameters are given in Table I. The selected predicted horizon is $h = 6$ h.

The predictive capability of the model is here illustrated with the flood of February 2002 (which is not in the data set used for model calibration). In Figure 6, a typical example of on-line forecasting with Hydromax is shown. We can see that Hydromax computes a short term prediction for 10 a.m. of 233 m^3/s (* in Figure 7), which is to be compared to the actual value of 160 m^3/s. Hydromax also computes a long term prediction over an horizon of 42 h (+ line) for the given scenario of future rainfalls and an "optimistic" prediction (o line) under the assumption that the rainfall will definitely stop.

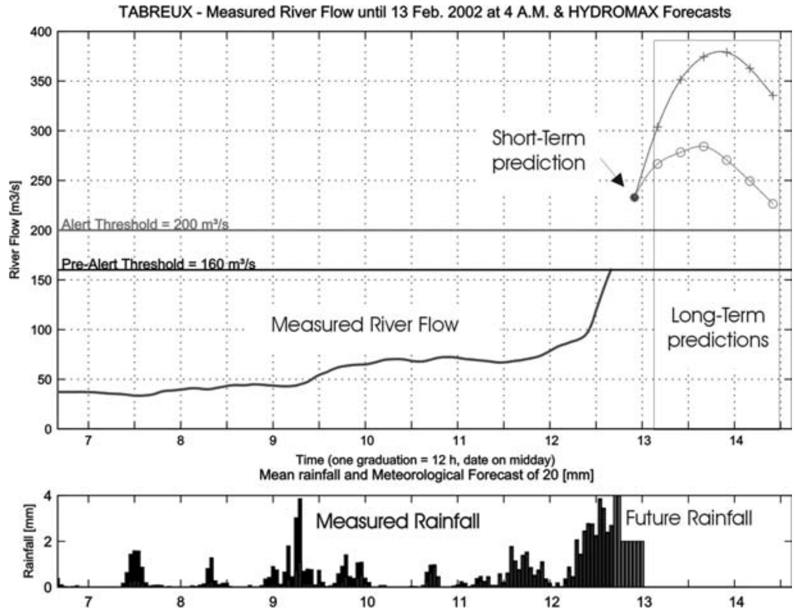

Figure 6. Example of Hydromax window: forecasting of Ourthe river (a Meuse river Tributary). Flow rate during the big flood of February 2002 (from 7 to 14 February).

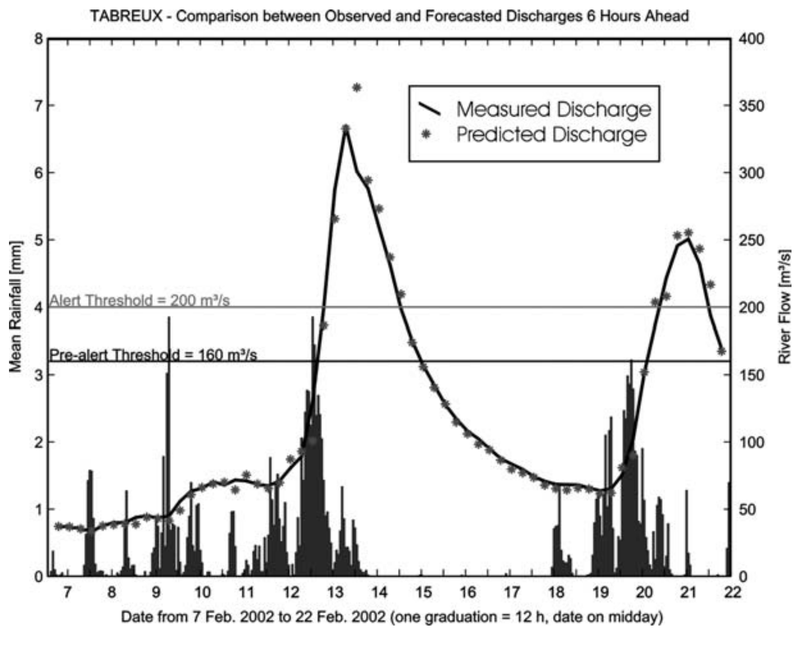

Figure 7. Tabreux-comparison between observed and forecasted discharges during the big flood of February 2002.

Table I. Tabreux-parameters of the model

α	β	$S_{\max}$ *[mm]*	a_1	a_2	b_1	b_2	b_3	b_4
0.00065	0.86	76	1.353	−0.41	2.382	0.896	0.202	0.993

Table II. Upper bound of the forecasting relative error at a level of 90%

Horizon	6 h ahead	12 h ahead	18 h ahead	24 h ahead	30 h ahead
$\left\|1-\frac{\hat{Q}}{Q}\right\| \leq$	0.07	0.13	0.18	0.22	0.32

In Figure 7, a comparison between the observed river flow discharges and the short-term predictions all along this flood of February 2002 is presented. Finally the statistical accuracy of Hydromax at a level of 90% is illustrated in Table II.

4. Real-Time Computation of Discharge Propagation and Water Levels: HYDROAXE

4.1. MATHEMATICAL MODEL

Hydroaxe is designed for real-time utilisation and flood forecasting. The mathematical model is thus a one-dimensional model, based on the Saint-Venant shallow-water Equations (4.1) and (4.2), in order to meet the short computation time requirements.

Mass conservation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=L\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=L\frac{\partial z}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{4.1}$$

Momentum conservation :

$$\frac{\partial Q}{\partial t}+\frac{2Q}{A}\frac{\partial Q}{\partial x}-L\frac{Q^2}{A^2}\frac{\partial h}{\partial x}-\frac{Q^2}{A^2}\frac{\partial A}{\partial x}\bigg|_{h=cst}+gA\frac{\partial z}{\partial x}+gAs_f=0 \tag{4.2}$$

where Q = discharge, A = cross section area, h = water depth, L = width of the section at the water level, z = level of the bottom, g = gravity constant and s_f = the friction slope.

The Saint-Venant equations are completed by the Exchange Discharge Model (Bousmar and Zech, 1999), which includes the effects of the momentum exchanges between the river and the floodplains:

Mass conservation:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_l=q_{in}-q_{out} \tag{4.3}$$

Momentum conservation:

$$\frac{\partial}{\partial t}(\rho AU) = -\frac{\partial}{\partial x}\left(\rho AU^2\right) - \rho gA\frac{\partial z}{\partial x} + \rho q_{\text{in}}u_{\text{l}} - \rho q_{\text{out}}U - \rho gAs_{\text{f}} \quad (4.4)$$

where q_{l} = lateral discharge, q_{in} = inflow component of the lateral discharge, q_{out} = outflow component, ρ = density of water, $U = Q/A$ = mean velocity, u_{l} = velocity component of the lateral inflow in the direction of the main flow. These two equations are solved with an implicit Preissmann scheme allowing rather large time steps.

4.2. GEOMETRICAL MODEL

The Meuse is considered as a network composed of elements such as "elementary reaches", "weirs", "junctions", "hydrographs" and "limnigraphs". Each element is represented by equations describing the relation between the water-level and the discharge evolution between two cross-sections, such as Equations (3) and (4) for the "elementary reach" elements (see Figure 8).

4.3. HYDROAXE DATA

First of all, Hydroaxe needs data describing the geometrical aspects of the problem. The 1D formulation of the model requires 1D data, i.e., cross-section profiles, derived from a DTM. This DTM is elaborated with a GIS (ArcView 3.2a GIS), and from the dense and accurate laser and sonar measurements of the topography (see Section 2.3). It is completed by delineating the bank limits and the flow limits, to separate the minor bed from the floodplains. Cross-sections are then computed. One cross-section profile every hundred metres seems enough to yield an accurate forecasting.

The cross-sections derived from the DTM are corrected: obstacles like the trees eventually detected by the laser are erased, and the gaps/bumps above the water level are filled/cut to avoid too many flow separations (see Figure 9a). They are also simplified: the number of points is decreased to allow a faster computation and to satisfy the real-time requirements of the model (see Figure 9b).

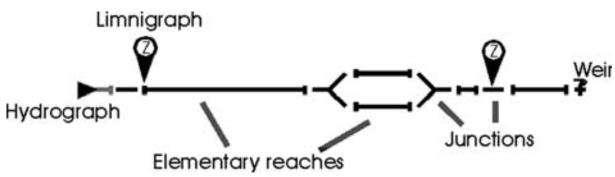

Figure 8. Geometrical network of a reach.

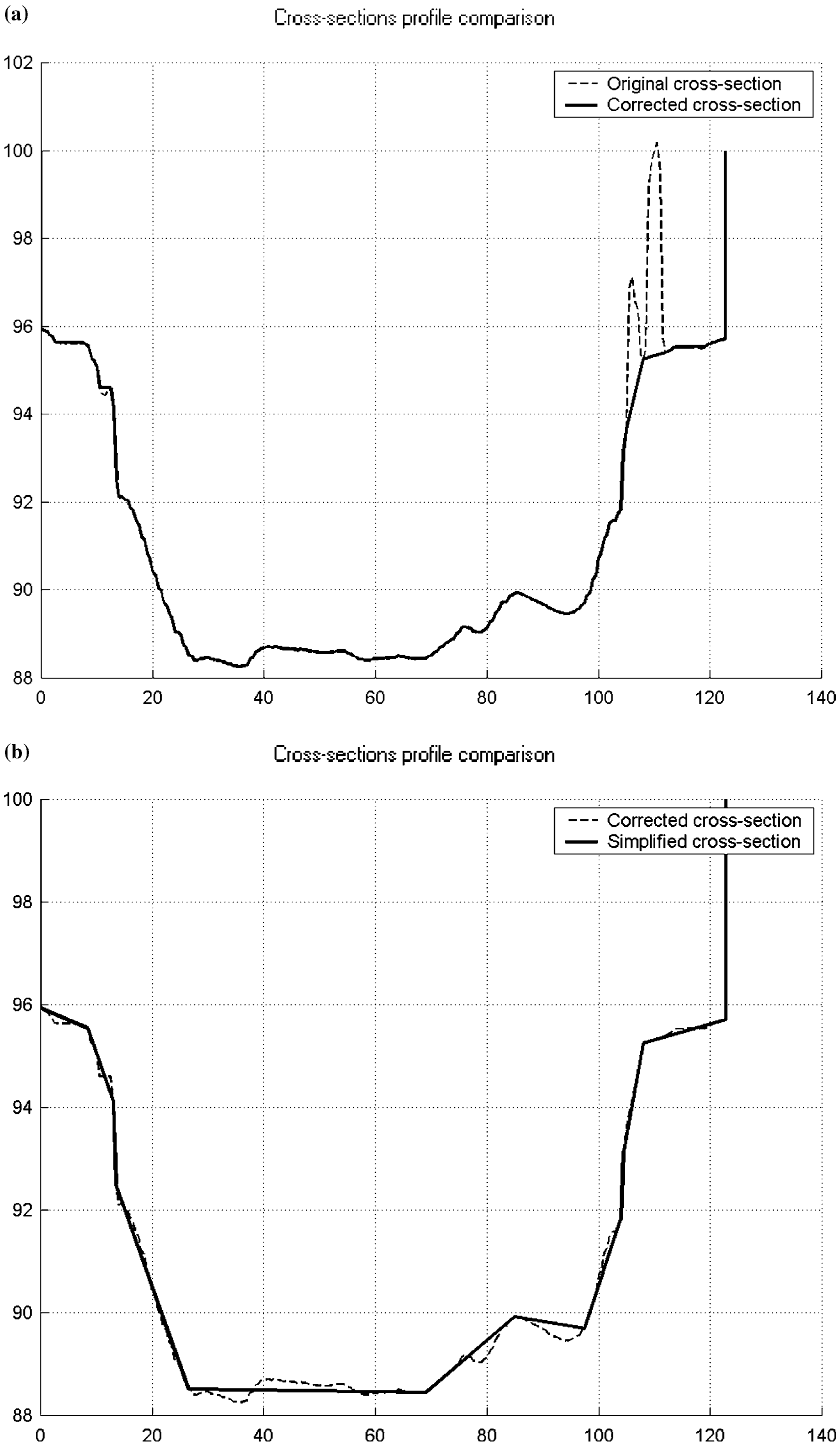

Figure 9. (a) Corrected cross-section. (b) Simplified cross-section.

Hydroaxe needs a set of discharges as upstream condition (measured in Chooz, see Figure 1) at the start of the Belgian Meuse network (French-Belgian border), and for its eight major tributaries. These discharges are produced by Hydromax, as explained in Section 3. The historic (= measured) part of these discharges covers 48 h, and the forecasting spreads on 18 h more. The discharges are injected in the model with some delay, corresponding to the flow time between the available hydrologic stations and the confluences of the tributaries (see Figure 1).

The downstream condition of Hydroaxe, i.e. the downstream water level, is given by the 48 last hourly level measurements at the downstream limit of the network (Ivoz; see Figure 1). The 18 next hourly levels needed by Hydroaxe are an average of the last 5 hourly measurements in Ivoz. Actually, simulations have shown that the downstream water level has little influence on the computed water levels except for the last downstream kilometres.

Several water-level stations are available along the Meuse river. The measured levels are introduced in Hydroaxe as controls and comparison tools for the user. This set of data is transmitted to Hydroaxe by Hydromax.

4.4. CALIBRATION

The major difficulty of practical use of Hydroaxe is the determination of the Manning's roughness coefficients for the main channel and the floodplains. This calibration requires three sets of data: an accurate measurement of the upstream discharge, the limnigraphs of the downstream and upstream water levels, for the concerned reaches. The first step consists in calibrating the roughness coefficient n_{min} of the main channel: the upstream discharge and the downstream water level are used by Hydroaxe to compute the upstream water level. The coefficient n_{min} is adapted until the difference between the computed and measured upstream water levels is minimised.

Once the roughness of the main channel is calibrated, the same process is applied to find a value n_{maj} for the floodplains. But this requires of course a flood event causing significant overflows. These operations have to be repeated each time that the minor bed geometry is changed (natural changes or dredgings).

4.5. THE HYDROAXE PROGRAM AND ITS RESULTS

The Hydroaxe user interface has been developed on a Unix platform using Matlab. Nevertheless, its computation kernel, named CatRiv (*CAlculation of Transients in RIVers*), is implemented in C++ language. Hydroaxe allows the user to choose the results he wants to produce with CatRiv, to visualize these results, and to store the water levels required for the computation of flooded areas with ArcView GIS.

Figure 10 represents a typical result window of Hydroaxe. For each selected cross-section (like Waulsort and Lustin in Figure 10), the user can observe the evolution of the water level and of the discharge for the 66 h of simulation. If water level and/or discharge measurements are available in this cross-section, it can also be displayed and compared with the model results. The 18 last hours of computation are the forecasted part of the results. It is of course the most useful information for SETHY to manage the flood event. Hydroaxe offers also the possibility to visualize the evolution of a water profile in a chosen reach. This evolution is illustrated by a movie of 66 images (1 per h), showing the bed of the river and the water level evolution.

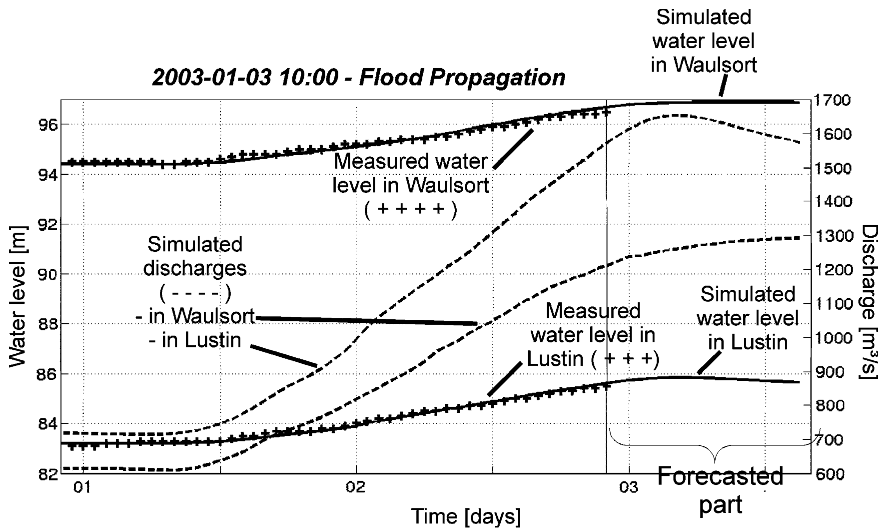

Figure 10. Hydroaxe result window: measured and simulated water levels in Waulsort and Lustin (2003-01-03).

5. Real-Time Computation of Flooded Areas with a GIS

5.1. INTERPOLATION OF WATER LEVELS

When the user works with Hydroaxe, he has the possibility to choose the moment and the reaches for which he wants to visualize the flooded areas. Hydroaxe can therefore transmit the needed water levels on the appropriate directory on the network. A separate computer can then carry out the treatment of these data with ArcView GIS.

The water level of each cross-section is extrapolated to five points of the sections: the intersection of the cross-section with the middle axis, with the bank limits and with the flow limit of the floodplains (see Figure 11). Then, these levels are interpolated and extrapolated to produce a water table. The interpolation is executed reach by reach, with the ArcView interpolation

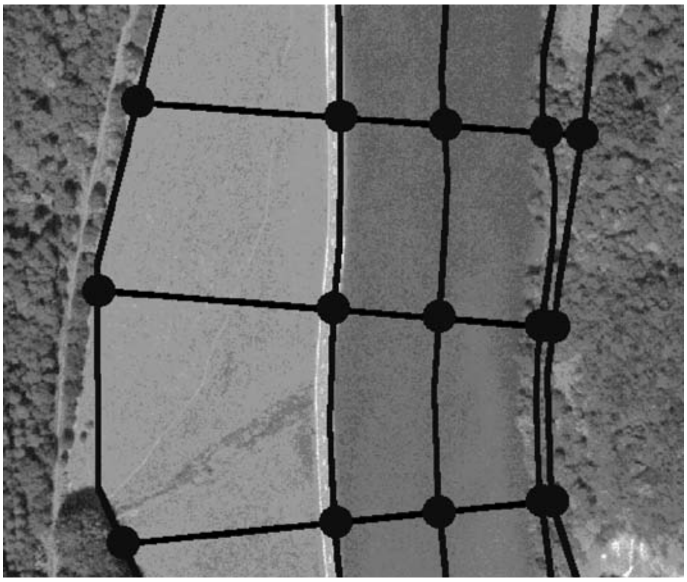

Figure 11. Five points of interpolation per cross-section.

procedures. A "tension spline" method of interpolation has been chosen, in order to minimize the curvatures and the slopes of the water surface.

5.2. COMPARISON WITH THE DIGITAL TERRAIN MODEL

Each reach of the model is represented by a digital model, based on sonar and laser surveys. These DTMs are grids of square cells, as well as the water tables. It is thus easy to produce the grid of the flooded areas of a reach: the DTM levels are subtracted from the water levels. Figure 12 shows a part of a DTM, i.e., the combination of the laser measurements (floodplains) and of the sonar measurements (main channel).

The map of flooded areas (see Figure 13) is corrected by the pointing of potentially flooded zones, i.e., the zones which are below the level of the water but separated from the river by natural or artificial obstacles.

5.3. VISUALIZATION

Besides the grid of the flooded areas, the user can display other useful information (ortho-images, the DTM and geographical maps) for a better identification of the location of risk. The flood map is accompanied by an adequate legend of the water depth.

This ArcView procedure has been designed to allow different resolutions of the final interpolated grid: cells from 2 to 10 m. The bigger cells require less computation time and are appropriate in crisis situations and very short-

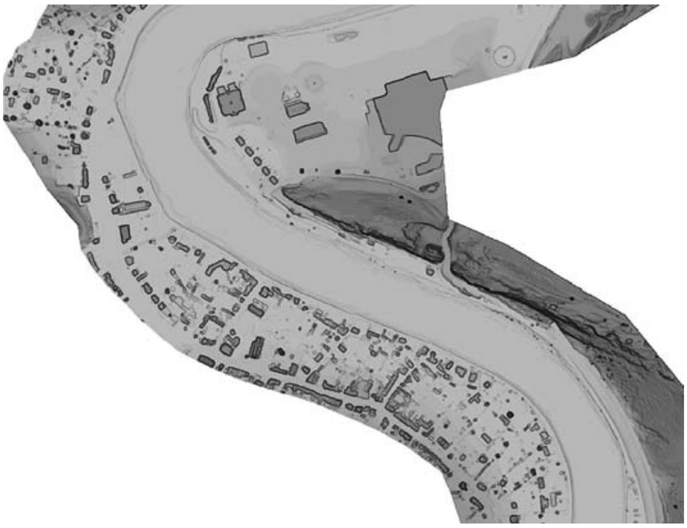

Figure 12. DTM example.

Figure 13. Flooded areas – typical results with ArcView GIS.

term forecasting. But the smallest cells are useful to produce more accurate flood maps for long-term projects.

6. Conclusion and Perspectives

Since their implementations at the crisis centre of SETHY, Hydromax and Hydroaxe have been successfully used to produce respectively, local river flow forecasts and simulations of discharge propagation and water levels all along the Meuse river.

The integration of these two real-time applications with an accurate DTM used by a GIS, forms an integrated tool to provide real-time flood-map on the Belgian Meuse. With this decision aid tool, SETHY is able to predict and to manage efficiently the consequences of a flood event. The coupled Hydromax and Hydroaxe models were used during the last two significant floods of the Meuse river, in February 2002 and January 2003. The water levels computed in January 2003 for the cities of Waulsort and Lustin are shown in Figure 10, illustrating the satisfactory behaviour of the models concerning the dynamics of the flood. The accuracy of the water levels could be improved, but is quite acceptable.

At the moment, one of the major limitations of the model application is the lack of accuracy on the upstream boundary condition (discharge at the French-Belgian border), which will be soon filled up with the setting up of a new flowmeter in Waulsort (see Figure 1). These new data should also allow a calibration of the Manning's coefficients, in order to improve the water level forecasting.

A next development will be the integration of automatic weather forecast in Hydromax, and the use of real-time rain data provided by weather radars. In fact, the rainfall, on a basin base, predicted by the Aladin-Belgium meteorological model (IRM – Belgian Royal Meteorological Institute) will soon be automatically full-integrated in the data base of SETHY.

Recently, all the weirs of the Meuse have been provided with sensors, giving in real-time the positions of the gates and the flapgates. These data are transmitted to SETHY and integrated in the database. Hydroaxe is then able to calculate the water level and the discharge passing through each weir. The next challenge is to take into account the programming of the controllers governing the moves of the gates. This will improve the efficiency of the model for the 18 h of prediction.

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