# Hydrological forecasting in real time: an experimental integrated approach

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*Abstract*—**One of the roles of geosciences is to provide the society with efficient tools that may diagnose or predict various environmental hazards. Floods are among such events, and hence there is an ongoing need to develop and improve hydrological models. However, especially in mountainous catchments which respond quickly to extreme rainfall, the need covers not only predictive models but also real-time systems that produce and publish up-to-date predictions with sub-hour update frequency. This includes forecasting both the hydrograph and inundation. The objective of the paper is to present a novel approach that integrates the real-time system for forecasting hydrograph, known as HydroProg, with the following two elements: the real-time inundation model that simulates the flood extent on the top of the Digital Elevation Model (DEM), referred to as FloodMap, and the on-demand monitoring of inundation using the Unmanned Aerial Vehicle (UAV). Although skills of the hydrograph prediction models are relatively easy to assess, the problem arises when we want to evaluate the performance of inundation models. This can be done as a near real-time procedure, initiated automatically when the HydroProg and the associated FloodMap produce flood alert, making use of the UAV for oblique photogrammetry. The UAV-taken aerial photographs enable production of orthophoto images which are utilized to check the accuracy of spatial predictions of water extent. The prototype of the comprehensive integrated system is presented, and the results are based on the experimental implementation of the HydroProg system in the upper Nysa Kłodzka River basin (SW Poland).**

## I. INTRODUCTION

The objective of this paper is to show how real-time hydrologic prediction systems may be combined with inundation models in order to compute a real-time prognoses of flood extent. The presentation is based on a recently designed and implemented hydrologic prediction system, known as HydroProg [1,2], which serves as a tool for issuing warnings against hydrologic hazards. Integrated with HydroProg is the FloodMap model [3,4,5,6], which allows one to carry out spatial simulations of inundation with several methodological approaches. The integration in question meets a key criterion of the real-time solutions, namely it works in an online fashion and offers predictions of inundation which are very frequently re-calculated and updated, following frequent calibration of hydrograph models. Unlike hydrograph predictions, inundation prognoses cannot be easily verified against true data. Hence, in order to check the correctness of the real-time inundation forecast, it is necessary to employ Unmanned Aerial Vehicles (UAVs) to produce ortophoto images that capture patterns of overbank flow [7]. Thus, the following elements may act in concert in a consecutive fashion: HydroProg-based real-time hydrograph predictions → FloodMap-based mapping of real-time hydrograph predictions into the spatial domain in order to produce real-time inundation prognoses → UAV-based verification of real-time inundation prediction.

Apart from HydroProg, there are numerous real-time hydrologic prediction systems and services. For instance, in the USA there exists the Advanced Hydrologic Prediction System [8], and for the Alpine region the MAP D-PHASE system has been deigned [9]. Although such systems serve a purpose of forecasting water levels or discharges, the above-mentioned integration of hydrograph real-time prediction with real-time inundation simulations, equipped with the UAV as a real-time verification tool, has not been developed so far.

The very initial test of the integration will be discussed in this paper, and the case study will focus on: (1) a single site of Gorzuchów located along the river of Ścinawka (left tributary of Nysa Kłodzka river in SW Poland) and (2) a single moderate peak flow event on 29 May 2014 – 2 June 2014. As there has been no flood since the launch of the HydroProg experiment for the upper Nysa Kłodzka river basin, herein we focus on high flow rather than inundation itself. However, even with such a limitation, we present a step-by-step concept of how HydroProg and FloodMap may be combined.

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## II. METHODS

### A. HydroProg and HydroProg-Kłodzko prototype

HydroProg is the acronym of a novel system – elaborated and designed at the University of Wrocław, Poland – which aims to issue warnings against hydrological hazards, such as peak flows. The system [1] integrates hydrometeorological gauging networks with numerous hydrologic models in order to produce hydrograph predictions based on individual models and on their multimodel ensemble. The prognoses are subsequently published online in an external web map service, and they are also used to issue warnings when peak flow is forecasted. The entire system may be called a rapid service as it works in real-time and offers predictions as well as the associated warnings which are calculated quickly, i.e. with the 15-minute update.

The general HydroProg infrastructure has been experimentally implemented for the upper Nysa Kłodzka river basin (SW Poland). This implementation, known also as the HydroProg-Kłodzko prototype, uses the real-time access to hydrometeorological data of the Local System for Flood Monitoring (Lokalny System Osłony Przeciwpowodziowej, LSOP) of Kłodzko County, Poland. Thus, HydroProg serves as an integrator of three elements: (1) the unique automatic gauging network installed in the mountains (LSOP), (2) a few hydrologic models, and (3) the web map service. The HydroProg-Kłodzko prototype generates predictions every 15 minutes, and this time step is used for: re-calibration of models, prediction update based on the newly calibrated models. The maximum lead time is equal to 3 hours, but intermediate prediction horizons are 15,30,…,180 minutes. The HydroProg-Kłodzko prototype has been launched on 1 August 2013, and since that time has been uninterruptedly working in a real-time fashion. Recent studies show that the HydroProg-Kłodzko prototype works well and is able to produce skillful real-time predictions of water level [2].

### B. FloodMap

A well-established hydrodynamic model, known as FloodMap [3,4,5,6], was used to derive the dynamics of flood inundation. River flow is modelled by the full solution of the 1D Saint-Venant equations. The 2D flood inundation model is raster-based and solves the inertial form of the 2D Shallow Water Equations. At the river/floodplain boundary, the model is tightly coupled by considering the mass and momentum exchange between the river flow and floodplain inundation. The 1D river flow model is based on the fixed bed model of Abbott and Basco [10]. The model solves the one-dimensional St. Venant equations for unsteady flow using the Preissmann Scheme (as reported in [11]), also known as an implicit box scheme because of the way it approximates hydraulic variables. The details of the model structure have been described in [3]. The 2D flood inundation model (FloodMap-Inertial) takes the same structure as the inertial model of Bates et al. [12], but with a slightly different approach to the calculation of time step. Neglecting the convective acceleration term in the Saint-Venant equation, the momentum equation becomes:

$$\frac{\partial q}{\partial t}+\frac{gh\partial(h+z)}{\partial x}+\frac{gn^2q^2}{R^{4/3}h}=0, \tag{1}$$

where $q$ is the flow per unit width, $g$ is the acceleration due to gravity, $R$ is the hydraulic radius, $z$ is the bed elevation, $h$ is the water depth and $n$ is the Manning's roughness coefficient. Discretizing the equation with respect to time produces:

$$\frac{q_{t+\Delta t}-q_t}{\Delta t}+\frac{gh_t\partial(h+z)}{\partial x}+\frac{gn^2q_t^2}{h_t^{7/3}}=0. \tag{2}$$

To further improve this, one of the $q_t$ in the friction term can be replaced by $q_{t+\Delta t}$ and this gives the explicit expression of the flow at the next time step:

$$q_{t+\Delta t}=\frac{q_t-gh_t\Delta t(\frac{\partial(h_t+z)}{\partial x})}{(1+gh_t\Delta tn^2q_t/h_t^{10/3})}. \tag{3}$$

The flow in the $x$ and $y$ directions is decoupled and take the same form. Discharge is evaluated at the cell edges and depth at the centre. To maintain model stability and minimize numerical diffusion, the Forward Courant-Freidrich-Levy Condition (FCFL) approach described in [6] for the diffusion-based version of FloodMap is used in the inertial model to calculate time step.

### C. UAV

There are numerous techniques for mapping inundation. Along with terrestrial methods, such as for instance surveying citizens who witnessed the event or observing geomorphological consequences of overbank flow, there are many remote sensing methods suitable for such purposes. They can be based either on satellite remote sensing [13] or aerial photography [14]. Recent advances in unmanned aerial systems open new possibilities for observing flood extent, and this is due to both the unprecedented spatial resolution of UAVs as well as a feasibility to react quickly to fly over the flooded terrain.

Among numerous UAVs there are ones classified as micro UAVs which – being lightweight and often revealing flexibility to take off and land in a complex terrain – offer an opportunity to carry out aerial survey over areas of considerable sizes. They serve a purpose of demonstration missions, but their bigger equivalents may do the same job over larger areas, and in the operational way. To carry out research reported in this paper, we use the micro fixed-wing UAV, swinglet CAM, manufactured by senseFly. Swinglet CAM is a flexible system that allows to take photographs with a pre-defined overlap with spatial resolution reaching 3 cm/px when the flight altitude is approximately 100 m above the take-off site. If there are no weather-related constraints, the flight time can be as high as 30-35 minutes. The UAV can be easily launched without special infrastructure, and this makes the device very suitable for geographical field research. Along with photo acquisition the UAV records numerous flight parameters, ranging from technical ones, through navigation-related values, to a few meteorological parameters. The UAV-acquired photographs can be geo-tagged, and hence both the Digital Surface Model (DSM) as well as orthophoto images may be generated using the Structure-from-Motion (SfM) procedure [15].

### *D. Integration*

The calibrated FloodMap model can be used to produce inundation predictions based on the HydroProg-generated water level prognoses, and the integration can work in real time. Firstly, when a new and up-to-date prediction of water level at a given gauge is produced by HydroProg, the HydroProg infrastructure sends the CSV file consisting of the forecasted hydrograph to the external FloodMap server. This happens automatically at fixed times. Hence, when there is a delay in the system, the older file (but, due to 15-minute update time, the file is usually still up-to-date) is utilized. Second, the predicted hydrograph is assumed as an input to the FloodMap model which is automatically run at fixed time intervals. The calculations of water depth in the spatial domain in the vicinity of the gauge (reach of a few hundred meters either side of the gauge) must be completed before the next 15-minute interval begins so that inundation predictions are up-to-date, as the hydrograph prognoses are. The UAV team can be requested to carry out field survey when inundation is predicted.

## III. CASE STUDY

### *A. Data*

The concept of integrating HydroProg with FloodMap, with its verification using UAV, is presented herein in the case study. We consider one site, i.e. the gauge in Gorzuchów (50.4853˚ N, 16.5714˚ E) located along the Ścinawka river (SW Poland), and we focus on the inundation along a 300 m reach at the gauging site, during a single peak flow event that occurred between 29 May 2014 and 2 June 2014 (Fig. 1A). As noted above, there has been no significant floodplain inundation since the launch of the

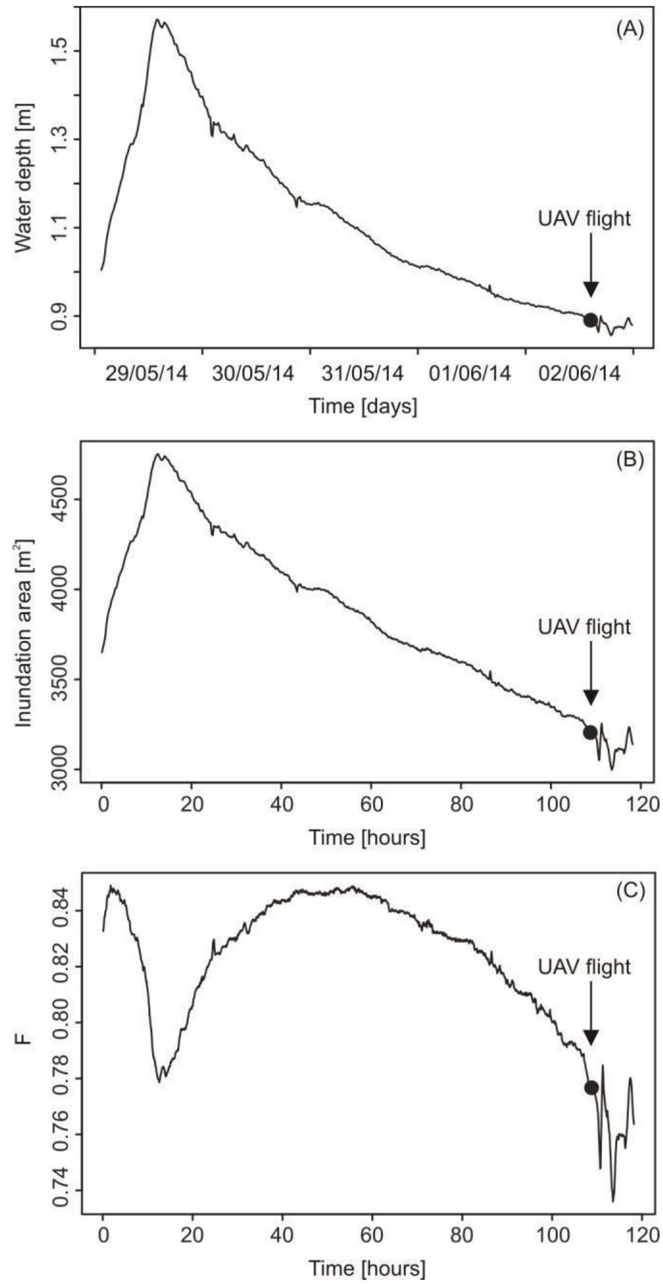


Fig. 1. Observed water depth at the Gorzuchów gauge between 29/05/2014 and 02/06/2014 (flow input to FloodMap) (A), total inundation area over time (B), time series of *F* statistics calculated against the UAV-derived inundation area at 14:30:00 UTC on 2 June 2014 – 109 hrs into the simulation (C).

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HydroProg-Kłodzko prototype. Thus, our exercise is limited to the HydroProg-FloodMap integration in the high flow situation. For the purpose of this paper, we show the FloodMap application using both the observed and predicted data as inputs.

The following datasets are inputs to the FloodMap model: HydroProg-based 3-hour predictions of water level in Gorzuchów, Digital Elevation Model (DEM) with the resolution of 1 meter based on processing of the Light Detection and Ranging (LiDAR) data, bed elevation data at the gauging station. The verification of the approach is based on orthophoto image for the Gorzuchów site, the production of which was based on the UAV survey carried out on 2 June 2014 (two flights at 07:11:29–07:41:49 UTC and 14:14:12–14:36:01 UTC; areas in the vicinity of the gauge were surveyed in the second flight; the average time of observation was assumed to be 14:30:00 UTC). The 2D version of the model is used in the simulation. A uniform water surface elevation is used to represent river flow. Given the mild slope of the site (~0.004) and length of the reach, this is considered as a valid assumption. The next section presents the results of model verification.

### *B. Initial results*

The total inundation area over time is presented in Fig. 1B. Although there is no significant floodplain inundation, the total area predicted to be wet follows the pattern of observed water depth at the gauging station. As water depth increases, more areas adjacent to the main river channel get inundated.

Fit statistics ($F$) is used to evaluate the degree of agreement between model prediction and observation, calculated as the ratio between the area both observed and predicted to be wet, and the total area either observed or simulated to be wet. The time series of $F$ is shown in Fig. 1C. The $F$ value of 77% is achieved for the validation point when UAV image was obtained, suggesting a good level of predictive ability. The lowest $F$ was found to be corresponding to the peak flow, which is likely due to larger extent found during the peak.

Fig. 2 shows the model simulated water extent at 14:30:00 UTC on 2 June 2014, superimposed on the UAV observation of terrain. The simulated extent agrees well with the UAV-based orthophoto image. The presence of trees and bushes along the bank makes the determination of flooded area uncertain in places. In order to show where the comparison is reliable, we sketched red lines in places where it was possible to unequivocally determine the river bank (hence, where presence of vegetation or orthophoto artifacts did not cover the true water signal). It is also apparent from Fig. 2 that the simulations correctly predicted the episode of flooding the bar in the vicinity of the bridge.

In addition, Fig. 2 presents the predicted water extent, calculated using the HydroProg-FloodMap integration approach.

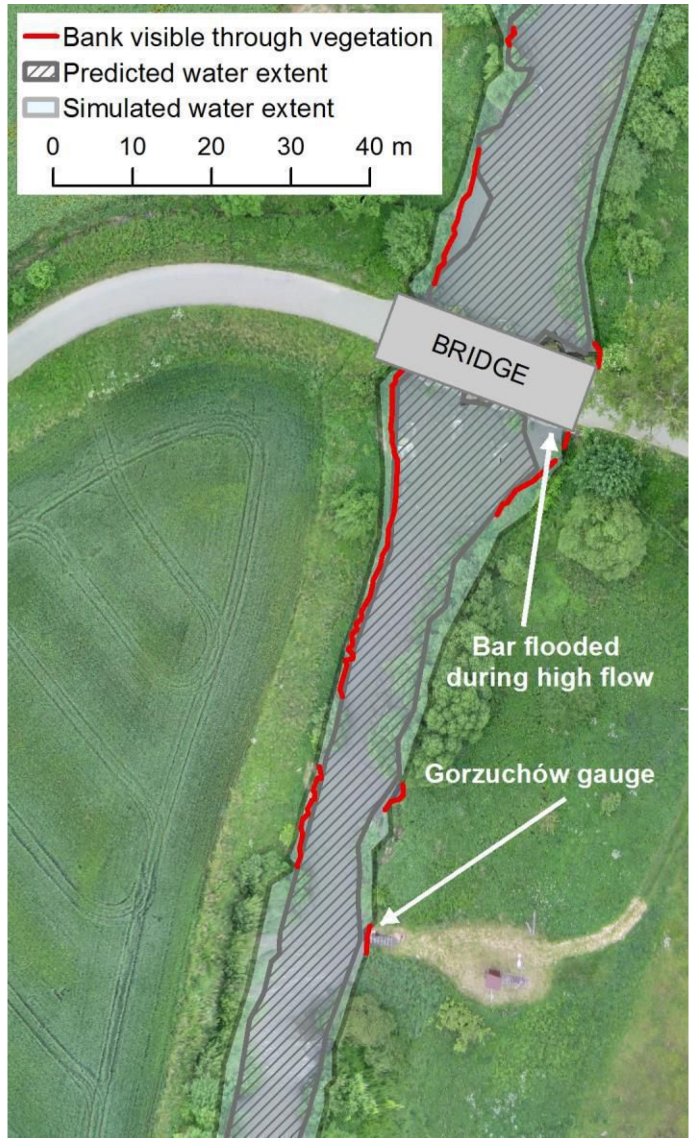


Fig. 2. Simulated water extent at 14:30:00 UTC on 2 June 2014 and predicted water extent (HydroProg-FloodMap) from 11:30:00 UTC into 14:30:00 UTC on 2 June 2014, both superimposed on the UAV-based orthophoto image serving as real observation (~14:30:00 UTC on 2 June 2014).

The HydroProg predictions of water level at the Gorzuchów gauge, calculated from 11:30:00 UTC into 14:30:00 UTC using the Vector Autoregressive (VAR) hydrologic model [16], became inputs to FloodMap, leading to the computation of 3-hour inundation prediction. The visual analysis of Fig. 2 leads to the conclusion that the predicted water extent is more accurate than the simulated one, particularly along the linear banks, however the prediction does not resolve the flooding of the bar in the vicinity of the bridge.

## IV. CONCLUSIONS

We presented the concept of integrating HydroProg with FloodMap in order to generate inundation predictions in real time. As it is difficult to evaluate the skillfulness of the inundation prediction, we believe that UAVs are able to serve a purpose of verifying the performance of such spatial hydrologic prognoses. The entire concept – hence the consecutive application of HydroProg, Floodmap and UAV – was shown herein to be feasible. Indeed, we presented the case study, based on one site and one peak flow event, which confirmed the usefulness of the approach. In particular, simulating high flow in the study site of Gorzuchów (along Ścinawka river, SW Poland) was successful, and the simulations were found to offer the 77% fit to the UAV data. The model was also able to reproduce site-specific episodes, such as flooding a bar. Forecasting high flow with the HydroProg-FloodMap approach was also found to be promising. Within this setup, water extent was predicted 3 hours ahead, leading to bigger agreement with linear banks observed by the UAV than in the case of water extent simulations. However, the HydroProg-FloodMap predictions of water extent failed to forecast flooding of the bar.

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