

High-Resolution 3-D Flood Information From Radar Imagery for Flood Hazard Management

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Abstract—This paper presents a remote-sensing-based steady-state flood inundation model to improve preventive flood-management strategies and flood disaster management. The Regression and Elevation-based Flood Information eXtraction (REFIX) model is based on regression analysis and uses a remotely sensed flood extent and a high-resolution floodplain digital elevation model to compute flood depths for a given flood event. The root mean squared error of the REFIX, compared to ground-surveyed high water marks, is 18 cm for the January 2003 flood event on the River Alzette floodplain (G.D. of Luxembourg), on which the model is developed. Applying the same methodology on a reach of the River Mosel, France, shows that for some more complex river configurations (in this case, a meandering river reach that contains a number of hydraulic structures), piecewise regression is required to yield more accurate flood water-line estimations. A comparison with a simulation from the Hydrologic Engineering Centers River Analysis System hydraulic flood model, calibrated on the same events, shows that, for both events, the REFIX model approximates the water line reliably.

Index Terms—Flood information mapping, light detecting and ranging (lidar) digital elevation model (DEM), regression analysis, synthetic aperture radar (SAR), SAR data uncertainty, 1-D hydraulic model.

I. INTRODUCTION

WITH THE onset of climate change implying an amplified frequency of floods in many regions of the world [1] and a steadily increasing number of economic assets being located within flood-prone areas, the need to understand and protect against flooding has become increasingly important for our society. The spatial characterization of hazard and risk is of paramount importance in any flood-management plan. Hence, an appropriate, rapid, and effective response to any flood-induced disaster is essential. Only remote sensing with its extensive spatial coverage in conjunction with field

measurements collected at high temporal resolution is capable of delivering the kind and quantity of information needed to meet these objectives most satisfactorily. Optical imagery has been successfully used in the past to extract flood areas [2]. However, given the rapid flood recession in small- to medium-sized catchments and weather conditions during events, flood detection with visible satellite imagery seems not feasible in many regions of the world. With its ability to acquire data during all meteorological conditions, day and night, and its capability to provide information about the extent of open water bodies, synthetic aperture radar (SAR) instruments present an alternative to optical imagery, aerial photography, and hydraulic model simulations for mapping flood extents over large areas and thus facilitate effective flood disaster management.

To date, the use of radar imagery is very often neglected in flood disaster management, as it is most of the time limited to a binary segmentation into flooded and nonflooded pixels and because of the inability of SAR to record flooding in urban areas due to the corner reflection principle. Furthermore, SAR images have a medium spatial resolution, are very often limited to a single frequency, are often difficult to orthorectify accurately, and tend to be geometrically and radiometrically distorted. Another important issue is the revisit time associated with the current radar satellites, which can take up to 35 days. Having SAR imagery acquired on the day of the flood is quite fortunate indeed. However, considering the 24- to 48-h image delivery time in case of a major (flood) disaster, SAR can be considered a very valuable and welcomed source of (flood) information. Moreover, with the numerous recent and upcoming SAR satellite missions (e.g., ALOS, RADARSAT-2, TerraSAR-X, and COSMO-SkyMed), more timely image delivery will be possible and a satellite constellation could be imagined.

As high-resolution digital elevation models (DEMs) become more readily available, it is possible to map not only flood extents but also flood depths for a given event. Complementary to the remote-sensing observations, a DEM can also be used to extract flooding under dense vegetation and forest cover [2], [3] and within residential areas. From a disaster management point of view, water depth information for a given flood event as well as flood visualization within urban areas is of paramount importance for obvious reasons such as property loss and damage, health issues related to standing waters, and the assessment of socioeconomic damages. Thus, for operational flood-management applications, the flood extent maps that are currently obtained with remote-sensing observations appear to be only of limited utility. Hence, retrieving water

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depth information by integrating the SAR imagery and high-resolution DEMs would present a significant step toward more effective flood management. In this context, Oberstadler *et al.* [4] overlay a flood extent on topographic contour lines to determine water levels. The vertical root mean squared error (RMSE) is 0.5 to 2 m with respect to field data. Brackenridge *et al.* [5] use the same approach and come to a similar conclusion by reporting a 1- to 2-m precision. Puech and Raclot [6] propose a rather complex methodology that is based on extensive fieldwork, hydraulic knowledge, and aerial photography interpretation skills. First, the floodplain is segmented into polygons on which water levels are supposed to be horizontal. Used in conjunction with topographic maps, interpretation of aerial photography followed by field measurement campaigns gives a vertical RMSE of 23 cm. Despite these encouraging results, the technique seems difficult to adapt to SAR images due to their inappropriate spatial resolution and their relatively high level of distortions. Hostache *et al.* [7] apply a depth-mapping method to a RADARSAT-HH SAR flood image of the 1997 flood on the Mosel River (France), which accounts for hydraulically sensitive zones and positional uncertainty of the SAR-derived flood map. They end up with an uncertainty between maximum and minimum water depth estimation of around 30 cm, on average.

II. MOTIVATION AND AVAILABLE DATA

A. Preliminary Study and Motivation

The following study presents a modified and improved version of a remote-sensing-based steady-state flood modeling approach proposed by Matgen *et al.* [3]. In a steady-state regime, a system (in this case, flood flow) is modeled assuming that hydraulic demands and boundary conditions do not change with respect to time. Matgen *et al.* [3] propose to draw cross sections perpendicular to the river channel from which to extract elevation data from a high-resolution light detecting and ranging (lidar) DEM at the boundaries of an ENVISAT-1 ASAR-derived extent of the January 2, 2003 flood event on the River Alzette (G.D. of Luxembourg). A moving average filter is applied to the data to smooth the decreasing elevation with river distance downstream.

The SAR-based model estimates a smoothed linear trend of water levels using multiple regression analysis with X and Y coordinates as the independent variables

$$H = aX + bY + c \quad (1)$$

where

- H estimated water height in m above sea level (asl);
- X map coordinate $X(m)$;
- Y map coordinate $Y(m)$;
- a, b, c regression coefficients.

The final vertical RMSE accuracy is 41 cm when validating the SAR model with field data. In contrast, the previously calibrated unsteady 1-D Hydrologic Engineering Centers River Analysis System (HEC-RAS) model [9] leads to an RMSE of 13 cm. This demonstrates that SAR data can be used to estimate a reliable flood water line but indicates that the hydraulic model

outperforms the SAR-based modeling approach. The higher performance of the HEC-RAS model is to be expected as it takes account of processes such as backwater effects, which dominate flow behavior locally and are neglected in the SAR-based modeling approach.

The objectives of this paper are adapted from the conclusions in [3].

- 1) Combine a triangular irregular network (TIN)-based method and the multiple regression model.
- 2) Address the challenges of using X and Y coordinates as independent inputs to the multiple regression analysis in the case of a meandering river reach, for example.
- 3) Investigate the pretreatment of the data, which may improve the results.

This paper presents an improvement of the methodology, thereby increasing the accuracy of the results.

In order to demonstrate this most objectively, a Regression and Elevation-based Flood Information eXtraction model (REFIX) is developed for a well-documented flood of the River Alzette and subsequently transferred to a reach of the River Mosel which experienced a medium-sized flood on February 28, 1997 recorded by RADARSAT in HH mode.

III. STUDY AREA AND AVAILABLE DATA

A. River Alzette Study Site

The study site at the River Alzette is located downstream of Luxembourg City between the gauging stations at Steinsel and Mersch (Fig. 1). It is characterized by a relatively large and flat floodplain. The villages along this river stretch have been subject to frequent flooding in the past two decades. The investigated flood event of January 2, 2003 has a peak discharge of approximately $69 \text{ m}^3 \cdot \text{s}^{-1}$. The reach is 10-km long and has an average floodplain width of approximately 300 m. It has a basin size of approximately 1175 km^2 , an average channel depth of around 4 m, and an average slope of 0.08%.

B. River Mosel Validation Site

The River Mosel has a long history of severe flooding. The model validation site at the River Mosel is located between Thionville, France and Perl, Germany (Fig. 1). It is characterized by a very flat floodplain with its villages situated at a slightly higher altitude than covered by the 1997 flood for which a peak discharge of around $1450 \text{ m}^3 \cdot \text{s}^{-1}$ was recorded. The reach is 16-km long and has an average width of approximately 3 km. It has a basin size of around 35500 km^2 , an average channel depth of around 8.5 m, and an average slope of 0.05%.

On both test sites, a water line of the flood events is simulated by the HEC-RAS model and compared to the REFIX-modeled water line. Although 1-D models are often criticized for their inability to modeling dynamic floodplain flows, such a model may often perform as well as a more complex 2-D model, and thus, in such a case, no justification based on data exists for the use of more complex models [10]. Moreover, the initial SAR-derived flood extents are compared with the REFIX-generated extents.

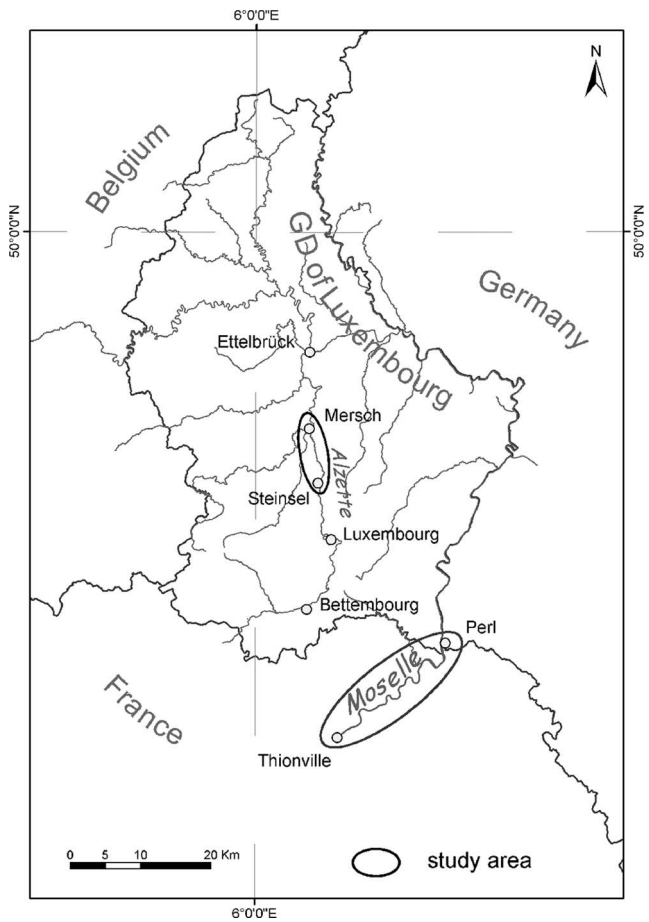


Fig. 1. River Alzette study site and River Moselle validation site.

The study database comprises the following. For the Alzette reach the following hold.

- 1) A single dual-polarized ENVISAT-1 ASAR image (VV, VH) of the January 2, 2003 event acquired with C-band at 5.3 GHz and with an incidence angle of 35° . The image was recorded at the time of flood peak, and it has a spatial resolution scaled from an initial 25–30 to 12.5 m using multilook filtering.
- 2) Continuous upstream (Steinsel) and downstream (Mersch) discharge measurements.
- 3) *In situ* measurements of maximum water height (cf. Fig. 6).
- 4) Digital photographs of the event.
- 5) Ninety one GPS reference marks of the maximum flood extent.
- 6) A lidar DEM of the floodplain at a spatial resolution of 2 m and a vertical accuracy of ± 15 cm, which is used to extract the water heights at the maximum flood extent.
- 7) Seventy four measured cross sections to determine channel geometry.

For the Moselle reach:

- 8) A single RADARSAT-HH SAR image of the February 28, 1997 event acquired with C-band and with an incidence angle of 28° . The image was recorded close to flood peak at a discharge of around $1360 \text{ m}^3 \cdot \text{s}^{-1}$, and it has a spatial resolution scaled from an initial 30 to 12.5 m.

- 9) A nonflooded aerial photography of 1999.
- 10) Continuous upstream (Uckange) and downstream (Perl) discharge and stage measurements.
- 11) A high-resolution DEM of the floodplain, obtained via a TIN generation from contour lines [7], at a spatial resolution of 7 m, and a vertical accuracy of ± 25 cm.
- 12) Sixty six measured cross sections to determine channel geometry.

It should be noted that both the HEC-RAS-simulated water line and the field-based maximum water heights only serve as validation sets and are not used to derive the regression-estimated water line. In other words, only the SAR image(s) and the DEM(s) are used to derive the water heights needed to estimate the flood water line and to subsequently generate a flood-depth map. For each flood event, the HEC-RAS model is set up using terrain geometry for cross-section profiling, flood hydrographs, and water stages as upstream and downstream boundary conditions [9]. For the Alzette River reach, the hydraulic model is calibrated using the ground-surveyed water levels. For the Moselle River, the calibration is performed using upstream, intermediate, and downstream gauging station-measured water stages, thereby testing the HEC-RAS capability of routing the flood wave accurately.

IV. MODEL DEVELOPMENT ON THE 2003 RIVER ALZETTE FLOOD EVENT

A. Methodology

Starting with the ASAR image, the REFIX-based flood-depth mapping approach follows the procedure illustrated in Fig. 2.

1) *Image Preprocessing*: The ASAR image acquired in dual polarization mode (VV, VH) is first orthorectified with an RMSE of below two pixels (25 m). Then, image speckle is reduced with a Frost filter (5×5) that uses image statistics to remove high-frequency noise while preserving the edges. The superiority of VH polarization over VV polarization for flood mapping is evident [11], given the fact that in VV mode, vertical objects (e.g., emerging low vegetation) are highlighted, whereas in VH mode, the horizontal nature of the smooth floodwater surface is being reflected.

For the REFIX to perform well, it is essential to smooth out as much SAR data uncertainty as possible while keeping enough information on the flood boundaries on which to allow water height extraction. After applying the edge-preserving filter, fluctuations between the left and right flood extent, which are assumed to be at level, remain. It is believed that the regression model smoothes out most of this uncertainty.

2) *Flood Boundary Delineation and Water-Line Modeling*: For a binary segmentation of the image, a simple but nonetheless effective and widely used thresholding [12] is applied. The threshold value is determined using GPS marks of the maximum flood extent. After flood boundary delineation, the lidar DEM is used to extract water heights for both riverbanks at each HEC-RAS cross section. If a systematic altitudinal difference between the left and right riverbank is present, the orthorectification accuracy and/or the flood area extraction method need to be reviewed. If all seems adequate, a flood water

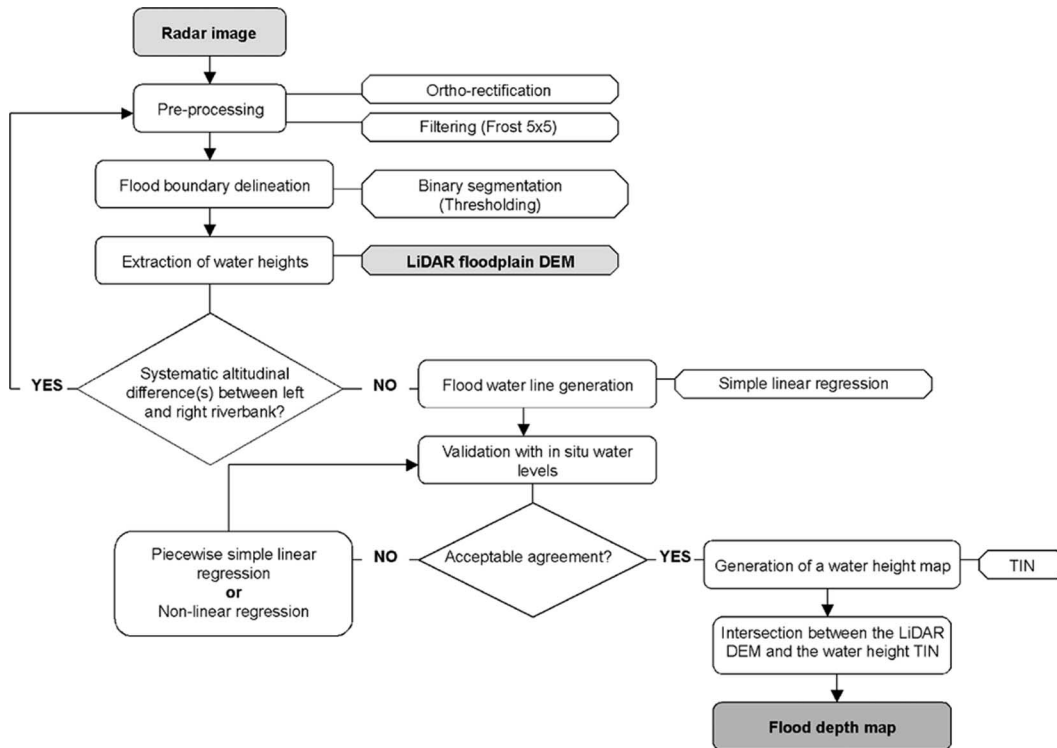


Fig. 2. REFIX methodology.

line can generally be estimated using a regression model (2) with the dependent variable being the water height extracted from the DEM and the independent variable the downstream river distance

$$H = a \cdot d + b \quad (2)$$

where

- H estimated water height (m asl);
- a slope of the regression (m/m), which of course changes with stream (bed) characteristics;
- d downstream river distance (m);
- b intercept (m).

It should be noted that for special cases under consideration, the model given by (2) may require certain adaptation (i.e., using piecewise linear or nonlinear regression analysis) to complex flow processes and interactions with local infrastructure in order to generate a more accurate flood water line, as will be illustrated by the River Mosel case study.

3) Integration of the Regression Model With a TIN:

a) Simple regression model: The advantage of simple linear regression as opposed to multiple linear regression [3] is that the former, by using the downstream distance instead of the X and Y image coordinates, accounts for and adapts to all changes in river orientation. However, when there is a significant change in riverbed slope or/and the presence of hydraulic structures, piecewise linear or nonlinear regression analysis is necessary to obtain a more accurate flood water line.

b) Water height TIN: As in this paper, the analysis is done without the ASAR pixel coordinates (cf. [3]), the generation of a 3-D water height map (or rather 2.5-D [13] with height being a function of x and y coordinates) from the estimated

flood water line requires the creation of a TIN mesh. For each river cross section, the water height is calculated through (1), and the cross sections are used as break lines, with the water line being linearly interpolated between successive cross sections.

The advantage of the TIN is that in this study approach, the water level is kept horizontal on each cross section, while at the same time, changes in river flow directions are respected, if needed.

Finally, to obtain the actual flood depths, the lidar DEM needs to be subtracted from the water height TIN.

B. Model Development Results

This part summarizes the application of the REFIX model to the Alzette flood event while illustrating the results and highlighting strengths and shortcomings. A general discussion will follow after validation of the model on the Mosel flood.

After orthorectification and filtering of the ASAR image, the flood area is extracted using the thresholding method (Fig. 3). The boundary of the ASAR-derived flood map matches the position of the GPS marks and agrees generally well with digital photography of the event.

Binary flood classification uncertainty of the SAR flood map can result either in over- or underdetection of flood. Overdetection is due to remaining speckle and relief shadow classified as flooded, whereas underdetection is the result of local roughness caused by, for example, strong winds, or water masking factors such as emerging or strong vegetation and buildings. Before the REFIX model is applied, areas of shadow may be reclassified as nonflooded according to slope and azimuth angle [8]. According to the study in [14], underdetection due to individual trees,

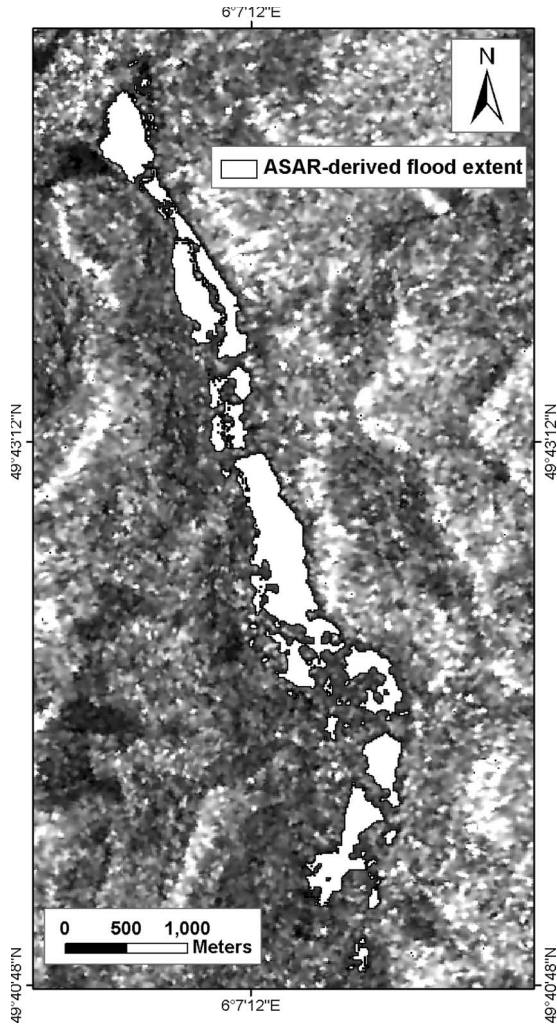


Fig. 3. 2003 Alzette river flood extracted from the ASAR-VH image.

forests, and buildings could be identified using a nonflooded aerial photograph.

After extraction of the water heights at the left and right flood extent, a scatter plot shows in general good agreement between the left and right riverbank heights (Fig. 4). It should be noted that a positional adjustment was performed on the original PRI image to eliminate most distortions. The georeferencing adjustment method used, which shifts the image until an acceptable agreement between left and right flood extent water level is found, is described in detail by Schumann *et al.* [15]. However, even after position fine tuning, there is still a considerable disagreement between the left and right riverbanks (up to 1.7 to 2.9 m) at two locations (around 4000 and 7500 m). At these locations, there is a sudden change in terrain slope on the right floodplain, which results from a positional error of the ASAR-derived flood extent. It should be noted that the georeferencing error of the ASAR image is one to two pixels.

This initial georectification error (i.e., a positional error) combined with the rather coarse spatial resolution of the ASAR image (scaled to 12.5 m) will worsen this effect.

Due to the coarse spatial resolution of the ASAR image, it is thought impossible to fine tune image georeferencing to the extent that the disagreement in heights between riverbanks

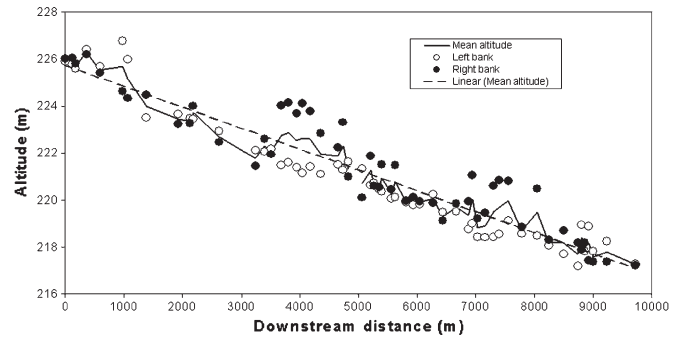


Fig. 4. Scatter plot of the DEM-derived water levels for both riverbanks (Alzette River).

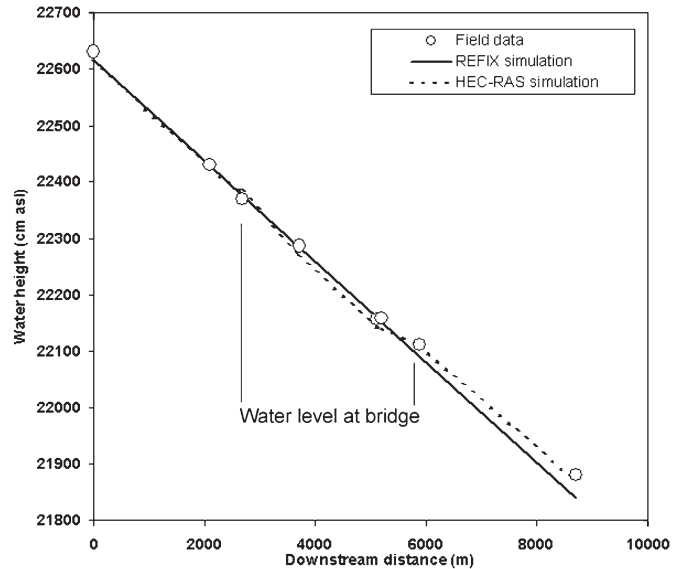


Fig. 5. Comparison between *in situ* water levels (in centimeters asl), the HEC-RAS-simulated water line, and the REFIX-modeled water line. N.B.: The position of each *in situ* high water mark is shown in Fig. 6.

would disappear. Moreover, it is expected that the linear regression model, which is applied to the mean altitude of the left and right riverbanks, is able to smooth out these height differences.

The model equation used to estimate the water heights that enable the generation of the water height TIN is of the form

$$H = -0.00089 \cdot d + 225.74. \quad (3)$$

Validating the estimated water line (dashed line on graph in Fig. 4) with well-distributed field data gives an RMSE of 18 cm. The REFIX water line when compared to that simulated with the HEC-RAS model has an RMSE of 16 cm (Fig. 5). Thus, it can be said that the proposed REFIX model is capable of generating a reliable water line for a given flood event and that the linear model chosen is appropriate.

As can be seen in Fig. 5, the HEC-RAS model is able to compute specific energy losses in the vicinity of hydraulic structures such as bridges that may occur along the river reach (e.g., the sudden nonlinear fall in water height at around 6000 m at the location of a hydraulic structure). Where such differences occur, the HEC-RAS model, of course, outperforms the REFIX

due to the fact that the former is able to perform unsteady flow simulations [9].

The water heights estimated by (3) for each river cross section are used to generate the water height TIN. Then, as a final step, the lidar DEM is subtracted from that TIN to map the actual flood depths (in centimeters). Fig. 6 illustrates both the water height map and the flood-depth map generated by the REFIX model. The flood-depth raster map represents the end product of this paper.

The accuracy of the REFIX flood extent when validated with the initial ASAR-derived flood map (Fig. 3) is 74%. It should be noted that, as one of the aims of the model is also to improve an initially incomplete SAR-derived flood map, the areas for which the accuracy of the REFIX map is assessed correspond only to areas for which flood detection from the initial ASAR image is relatively certain. Areas, where flood detection on a SAR image is near steeply rising terrain, roads, railways, forests, and near emerging vegetation, need to be eliminated before assessing the accuracy of the REFIX, as they represent a considerable level of uncertainty. In the case of the Alzette River reach, there are only two zones of flood-detection uncertainty. They exhibit a sudden change in terrain slope near roads and railways (see Fig. 4). There are neither trees nor hydraulic structures in this reach that need to be accounted for.

The results demonstrate that the REFIX model is indeed capable of estimating the water line of a given flood event reliably and accurately and thus can be used to produce an event-representative flood-depth map.

A particular strength of the REFIX model, compared to the modeling approach by Matgen *et al.* [3], is that neither a fluctuation in water level at any given cross section due to the positional uncertainty of the SAR-derived flood extent, nor changes in river flow orientation which seem to be a significant issue.

V. APPLICATION OF THE REFIX MODEL TO THE 1997 RIVER MOSEL FLOOD EVENT

A transfer of the REFIX model to other flood prone areas is needed to confirm the validity of the approach in other more hydraulically complex and/or more meandering reaches. In this context, the REFIX model is applied to the 1997 flood event on a reach of the River Mosel.

This validation enables several important issues to be discussed.

- 1) What is the effect of a coarser floodplain DEM on flood-depth estimation?
- 2) What effects do hydraulic structures and densely vegetated areas have on SAR-derived water heights?
- 3) What is the impact of a meandering reach?
- 4) What is the effect of a change in river slope?

The REFIX model is validated with the February 28, 1997 flood event on the River Mosel recorded by RADARSAT SAR in HH mode, a preferred polarization for flood inundation mapping [11]. Moreover, the Mosel basin is thirty times the size of the Alzette basin (35 500 km² compared to 1175 km²). Furthermore, the reach of the River Mosel is characterized by a much higher degree of sinuosity and by a much larger

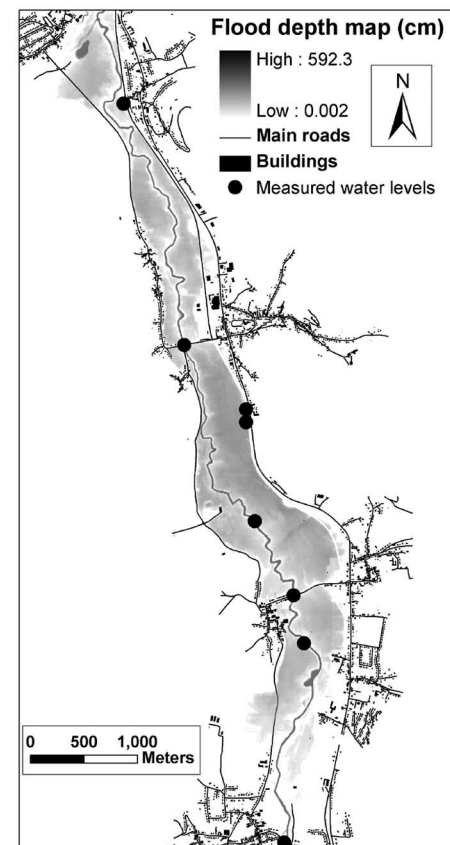
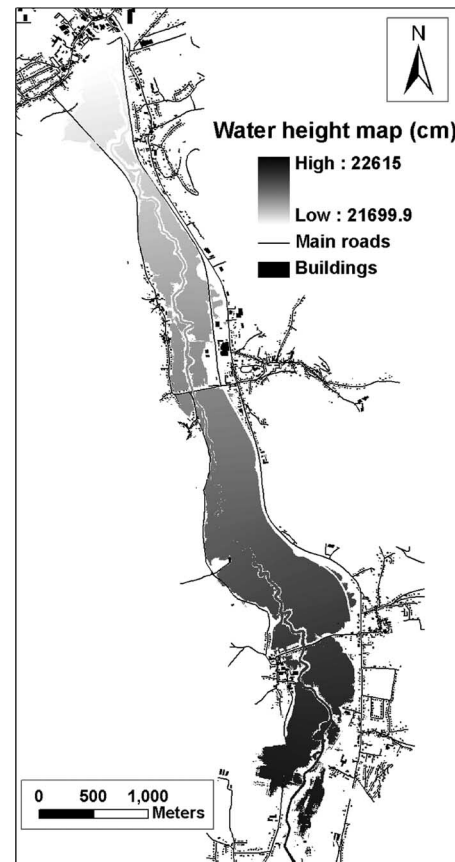


Fig. 6. REFIX-generated maps. The water height map (top) is the result of the TIN converted to a raster map. The flood-depth map (bottom) represents the subtraction of the lidar DEM from the water height raster map.

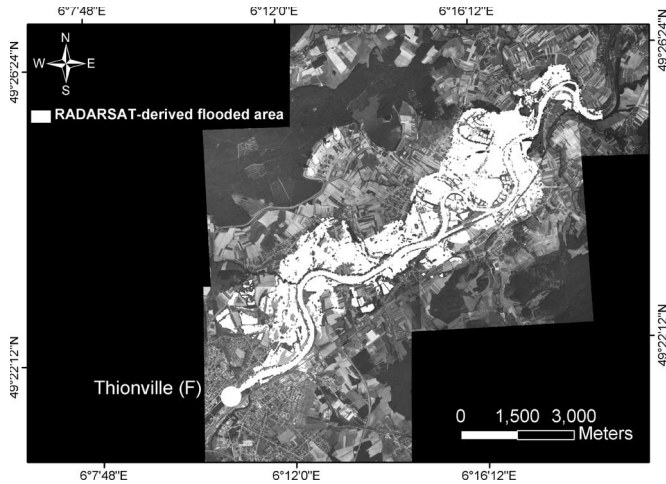


Fig. 7. RADARSAT HH-derived flood map of the River Mosel flood on February 28, 1997 (after [7]).

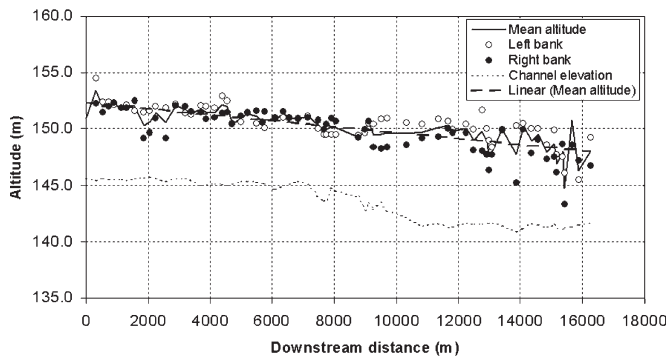


Fig. 8. Scatter plot of the DEM-derived water levels for both riverbanks (Mosel River).

floodplain width, and there are many hydraulic structures located within the studied reach.

Fig. 7 shows the RADARSAT HH-derived flood map [7]. The map is extracted using a fuzzy rule-based thresholding value given by the pixel distribution histogram (located between a maximum -12 dB and a minimum -14 dB). It should be noted that in terms of rapid flood detection, the superiority of HH mode increases the certainty with which flooding can be extracted in areas of low emerging vegetation. However, this does not at all solve the problem of SAR (C-band) flood monitoring uncertainties in areas of forests, roads, hydraulic structures, and terrain irregularities (e.g., abrupt steep slopes).

For the validation of the REFIX, the exact same procedure as for the Alzette reach (cf. Fig. 2) is applied. Fig. 8 plots the left and right flood extent elevation, extracted from a 7-m DEM, against downstream river distance at each HEC-RAS cross section. A linear regression model is again applied to the mean altitude and is of the form

$$H = -0.0003 \cdot d + 152.3. \tag{4}$$

Remaining local fluctuations in water heights between the left and right riverbanks implicitly reflect positional uncertainty of the SAR-derived flood map. A detailed land cover analysis of a 1999 nonflooded aerial photography of the study area

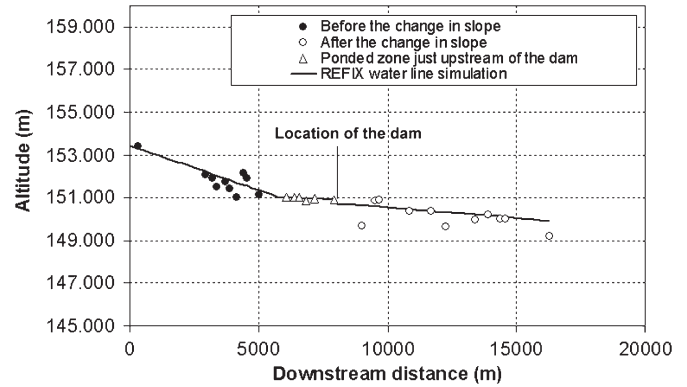


Fig. 9. Scatter plot of the piecewise linear regression models before and after the position of the dam. N.B.: Areas of SAR data uncertainty have been eliminated.

revealed that the scattering, which is a result of a significant difference between left and right bank elevation, is located around areas of roads, forests, and hydraulic structures, which was not the case for the Alzette River reach. In such areas, a minor positional error of the flood extent will again inevitably lead to over- or underestimation of the actual water height. Thus, these areas need to be ignored in order to obtain a more event-representative flood water line. The systematic higher elevation on the left bank from 8000 m onward results from the fact that forest trees cover all of the right extent.

Moreover, the minimum channel elevation (Fig. 8) shows a sudden change in slope at around 8000 m downstream at the position of a dam. After having accounted for areas of considerable SAR data uncertainty, the presence of the dam imposes a piecewise linear regression procedure that is applied to the mean of the right and left riverbank altitudes. Fig. 9 illustrates the piecewise linear trends of the mean altitude before and after the position of the dam. Also, a “ponded zone,” i.e., a zone where water backs up upstream of some construction so that the gradient becomes less than downstream, needs to be considered in order to get an accurate water-line simulation.

The new regression models obtained after considering the change in slope at the position of the dam are as follows:

$$H = -0.00042 \cdot d + 153.32, \quad \text{before the “ponded zone”} \tag{5a}$$

$$H = -0.000053 \cdot d + 151.32, \quad \text{“ponded zone”} \tag{5b}$$

$$H = -0.00013 \cdot d + 151.68, \quad \text{downstream of the dam.} \tag{5c}$$

In order to assure hydraulic coherence in terms of a continuous flow downstream, the three regression models (5a)–(5c) are connected. Then, the water height (H) is estimated for each HEC-RAS cross section at a given downstream distance (d).

The REFIX simulation of the flood water line, after considering only those cross sections areas for which SAR flood detection is relatively certain and after taking into account the change in riverbed slope, is provided in Fig. 10. As no field-based water levels are available for the Mosel validation site, a HEC-RAS simulation is taken to validate the REFIX-simulated

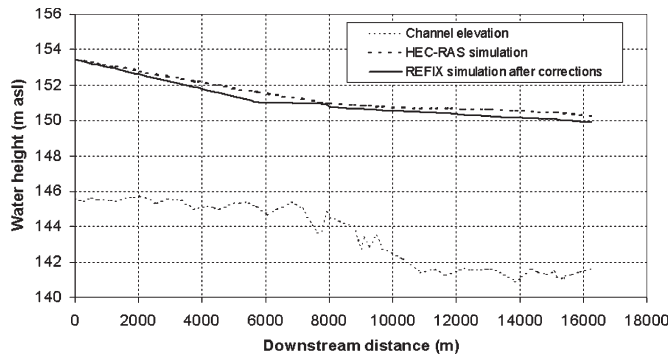


Fig. 10. Comparison between the HEC-RAS-simulated water line and the REFIX-simulated water line.

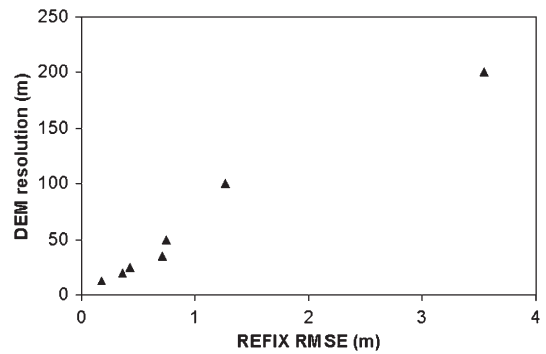


Fig. 12. Impact of different DEM spatial resolutions (i.e., cell sizes) on the flood-depth RMSE of the REFIX model.

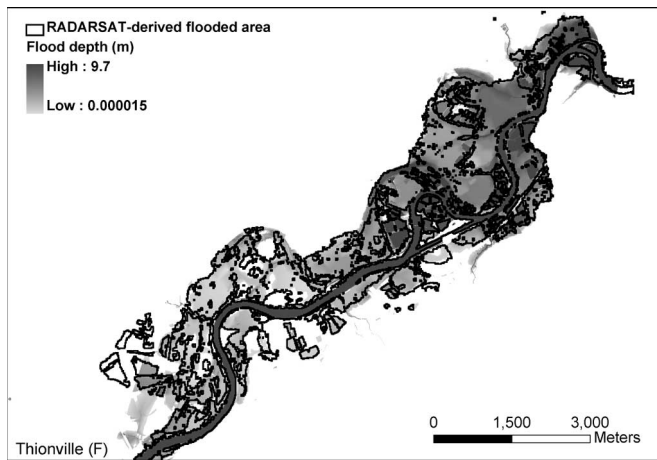


Fig. 11. Comparison between REFIX-generated map extent and initial RADARSAT SAR-derived extent.

water level at each of the 66 considered cross sections. The vertical RMSE in water-level estimation for the Mosel reach is 31 cm.

Fig. 11 shows the REFIX-generated flood depth. In terms of flood extent estimation, the importance of considering those areas that may distort the SAR signal and incorporating changes in riverbed slope becomes even more obvious. The percentage agreement between the REFIX-generated extent and the initial SAR-derived extent (cf. Fig. 7) is 82%.

VI. GENERAL DISCUSSION

REFIX-derived 2-D (flood area and extent) and 2.5-D (flood depth) flood information can aid in flood risk management and mitigation. This paper demonstrates that the integration of moderate (SAR) and high (lidar) resolution remote sensing can provide an innovative solution in terms of more efficient flood disaster management.

Despite the improvement over the preliminary study [3] as well as the high performance of the REFIX model itself, several concluding remarks should be noted. The following list gives the major error sources that impact on the determination of water height and thus flood depth.

- 1) The horizontal (i.e., spatial) as well as the vertical resolution of the DEM determines the accuracy and reliability

of the modeled results (Fig. 12). In Fig. 12, the spatial resolution of the lidar DEM was resampled to different cell sizes to illustrate its impact on the vertical RMSE of the REFIX model, in the case of the Alzette. A floodplain DEM of a high spatial resolution (≤ 25 m) and a vertical accuracy of at least 0.5 m (which seems appropriate for local scale flood disaster management) should be available when modeling on small and heterogeneous river reaches. However, in the case of large and more topographically homogeneous river basins, a DEM of a coarser spatial and also vertical resolution, e.g., an InSAR-generated DEM, may still give reasonable results. However, more globally available DEMs such as the SRTM DEM series require more detailed investigation as to the suitability of their vertical accuracy, which exceeds 6 m on average [16].

- 2) The satellite image used has to be of high quality. This paper shows that an image pixel uncertainty of 25–30 m is considerable. The user has to bear in mind that subsampling the image to finer spatial resolutions will not improve the quality of the image, and that after applying a special SAR filter, an important information may be lost.
- 3) The georeferencing should be accurate. Small errors in this processing step can result in large inaccuracies and consequently entail false conclusions.
- 4) If required, piecewise linear or nonlinear regression analysis should be applied to the DEM-derived data in order to model the water line more accurately.
- 5) It should be verified whether or not the hypothesis of horizontal water levels on each cross section is valid.

It should also be noted that the moderate agreement between the SAR-derived flood extent and the REFIX extent, in the case of the Alzette River, results from the fact that there is a considerably large area where 2-D complex floodplain flow processes cannot be automatically predicted by the REFIX. This obviously decreases the level of agreement and stresses the need to address the following research question:

Is there a need to account for 2-D in floodplain flows with the REFIX model?

Complexity in floodplain flows, which the 1-D HEC-RAS model may often oversimplify, could be addressed by the REFIX model. Polygons could be drawn for such areas to encircle SAR pixels for which water heights may be at level

with the surrounding areas in the same floodplain but not necessarily at level perpendicular to the channel. This in turn highlights the question to determine the optimal complexity for a given region (e.g., 1-D or 2-D flow pattern) and data set, and may be achieved through a decision tree approach. The REFIX can serve as a basis for such an approach. The procedure is nearly identical to that adopted for the Mosel reach in this paper. A given region could be modeled with the REFIX and then evaluated to determine in which areas there is a considerable error. This error is an indication of where to model differently. Identifying the nature of the error, e.g., nonconnected areas or backwater effect, is necessary to choose the right modeling approach for the given region.

The case study of the Mosel River illustrates well that considering the SAR data uncertainty and adapting the REFIX to changes in riverbed geometry and to hydraulic structures are necessary to assure model flexibility in more complex environments. In other words, care must be taken to select areas where flood detection from SAR imagery is relatively certain and to define hydraulically sensitive zones in order to assure a vertical RMSE of below 50 cm (cf. Figs. 5 and 10), which seems sensible for flood-management purposes. Here, once more, an important question emerges, namely “how far can model complexity go for model efficiency to be still acceptable?”

When hydraulic structures become dominant in a given area, the preference should be given to a hydraulic flow routing model, such as the HEC-RAS, which is dynamic and more flexible. It has been shown (cf. Fig. 5) that a well-calibrated hydraulic flood model seems to be the most reliable solution most of the time with an RMSE of 13 cm, when only one solution to the problem is desirable. However, it is clear that the most reliable and appropriate solution is an integration of several solutions to the same problem. Therefore, for example, for an effective flood disaster management plan or strategy, it is advisable to combine hydraulic flood modeling, *in situ* measurements, remote sensing, and of course event and terrain knowledge.

In the context of an outlook on potential REFIX-based flood disaster management applications, Matgen *et al.* [3] show that in vegetated areas where SAR signals are often scattered, the REFIX modeling approach could be applied to map the flooding. As buildings also distort the SAR signal, it is possible to extract flooding from urban areas using the REFIX. However, this requires reliable flood extraction downstream and upstream of the urban area, as otherwise no representative flood water line can be derived inside the urban space. Moreover, it is assumed that this would only work for small- or medium-sized towns or villages. For larger towns and cities, it may become impossible to estimate the general trend of the water line within the urbanized area.

Not only in the field of flood disaster management but also for physically based hydraulic model calibration purposes can the REFIX be used effectively. As for such models, point measurements may be insufficient; they could be calibrated with REFIX-based flood-depth uncertainty bounds derived from regression confidence intervals. This would allow a much more reliable model to be used for flood fore-

casting and thus risk mitigation. In this context, Horritt [17] points out that to date, calibration and validation of flood models are hindered by a lack of adequate data. Only very few studies, e.g., [10], and [17]–[21], have shown that SAR-derived flood maps are able to constrain the calibration uncertainties in flood inundation models. Werner *et al.* [22] have demonstrated that water depth is able to constrain the uncertainty in flood inundation models more efficiently than binary patterns.

VII. CONCLUSION

Compared to a preliminary study by Matgen *et al.* [3], the newly proposed REFIX model, by means of regression analysis, presents numerous advantages and is able to reliably estimate the water line of the January 2, 2003 River Alzette flood event. A lot of fluctuations in the decreasing trend of water-level downstream are smoothed out by the simple regression. Even a more complex flood event on the Mosel River is modeled in a reliable and coherent way.

The high model performance is above all due to the availability of very high-resolution and high-precision lidar DEMs. Apart from presenting a promising alternative to rapid flood risk management and response, initial tests show that the REFIX model can improve fractured or incomplete flood maps derived from SAR imagery [23].

Also, it should be noted that this paper demonstrates the use of moderate resolution SAR data on small-scale reaches (approximately 356 km² for the Alzette River reach) as opposed to macroscale basins, which are very often preferred to demonstrate the use of SAR remote sensing given their vast drainage areas. Moreover, the availability of InSAR DEMs means that the REFIX may become a valuable SAR-based flood information and mapping tool, which could be applied globally. The integration with InSAR DEMs could make the REFIX model a potential tool for ungauged basins.

Probably in the near future, new SAR satellites could help to make even more progress in the field of hydrology and flood risk management, as the main obstacles to date are the spatial resolution, the microwave frequencies, the polarization modes where HH should be the preferred mode given the horizontal nature of a water surface, and both the geometric and radiometric qualities of the radar images currently available. As to the revisit time issue, a constellation of future SAR satellites could provide timely images during a major flood event.

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