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Advanced analysis and integration of remote sensing and *in situ* data for flood monitoring

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ABSTRACT

The increasingly occurrence of flood events claims our capacity to enhance risk reduction and damage mitigation. The current large availability of satellite data constitutes a fundamental resource for disciplines such as fluvial geomorphology and hydrology that exploit the new technologies and techniques to develop innovative approaches for improving flood phenomenon investigation. The present work, extracted from a PhD thesis, describes the application of advanced analyses and data integrations to detect and to monitor flood events. The new data fusion methodologies are tested in various areas, at different spatial and temporal scales, in various surface conditions. The results (flood extent maps, geomorphic index maps, flood inundation maps, etc.) demonstrate the advantage to use complementary information sources and the progress in addressing scientific research towards the production of operational systems.

KEYWORDS: Flood monitoring, integrated methodologies, innovative system, applicative tools.

INTRODUCTION

Increasingly frequent and disastrous flood events impose studies for flood analysis and monitoring. The need to minimize damages in case of floods is requested by the *European Directive 2007/60/European-Commission* that invites all member States to produce flood hazard maps, establishing a first Community coordination program on flood risk assessment. Several researchers investigate flood phenomena at local and global scale by involving various disciplinary sectors for the development of new techniques and technologies for flood monitoring (Pappenberger et al., 2012; Wohl, 2014; Dottori et al., 2016; Rinaldi et al., 2016; Refice et al., 2017). During the last decades, satellite remote sensing played a functional role in the investigation of alluvial events, thanks to its capability to obtain high spatial resolution information in relative short time intervals and on wide areas, which sometimes are not accessible from the ground. These potentialities become fundamental, in the observation of flood events, to detect the effects of the inundation, such as water extent and morphological changes, also to contribute to identify the causes and to improve flood forecast (Lai et al., 2014; Schumann et al., 2015; Grimaldi et al., 2016; Revilla-Romero et al., 2016). The availability of a big amount of remote sensing data has therefore allowed the scientific community to improve the knowledge regarding the flood phenomenon through the application of remote sensing in geomorphology and hydrology (Rahman & Di, 2016; Capolongo et al., 2018; Domeneghetti et al., 2018). This progress towards a multidisciplinary approach to flood analysis demonstrates the improvement in flood phenomenon investigation, suggesting that data fusion methodologies can enhance flood monitoring through a better quality of flood detection and forecast. The present work aims to propose and to experiment innovative methodologies for flood event investigation and monitoring by applying a holistic approach able to consider, elaborate and intersect different and complementary data sources.

DATA AND METHODS

The following sections describe case studies set in various areas where flood events are observed and analysed at different spatial and temporal scales and in diverse surface conditions so that data and methods can be better applied and combined.

Case Study 1. Flood extent detection is experimented in a remote and recurrently flooded vegetated area. The study area 1 is the region at the confluence of (Lower) Zambezi River with its tributary, Shire River, in Zambezi River Basin (Mozambique). A variegated surface cover characterizes the area: wetlands, (open and closed) forests, croplands, grasslands (herbaceous and shrubs), urban zones (Fig. 1a).

Case Study 2. The experimental application of sediment connectivity index map in flood monitoring is tested in a large recurrently inundated floodplain. The study area 2 is the region at the confluence of (Lower) Severn River with its tributaries, Teme and Avon Rivers, in Severn River Basin (UK). In the area, located in the valley bottom (Fig. 2a) and characterized by a particularly dense hydrographic network, many flood events occurred in 2007-2010.

Case Study 3. Flood extent monitoring in fluvial sub-catchments is experimented in the same area and during the same flood events of Case study 2.

Case study 4. A “global inundation risk” is estimated in the overall large territory of Italy (study area 3), where many rivers shape fluvial valleys and floodplains, increasingly inundated in the last decades.

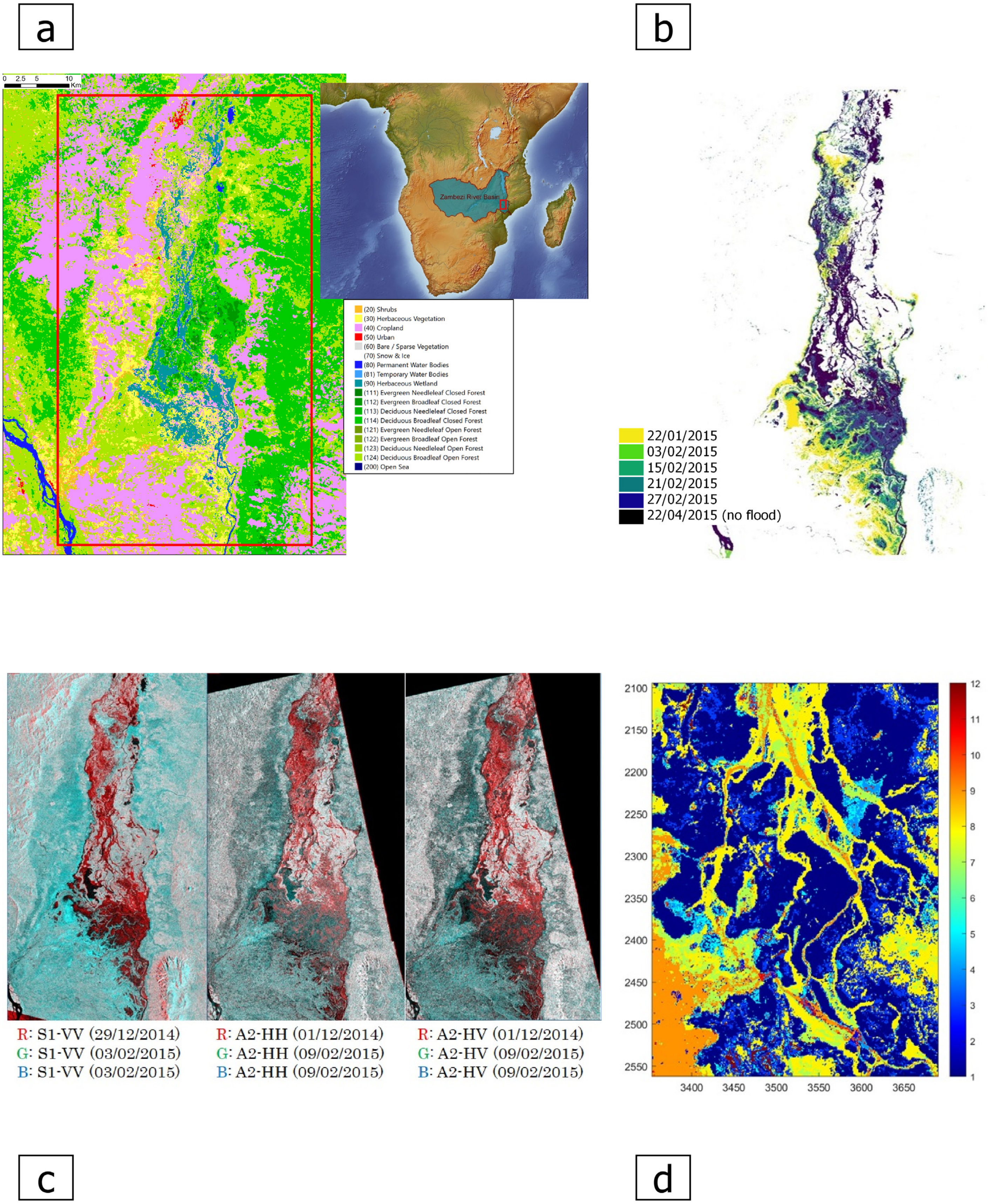

Fig. 1 - a. Study area 1 (red box) in Zambezi River Basin with Corine Land Cover. b. Sentinel-1 multi-temporal flood map obtained by DAFNE algorithm. From Refice et al., 2020, Fig. 2 (modified). c. RGB combination for S-1, ALOS-2 HH, ALOS-2 HV. Red areas: decrease of backscatter. Cyan areas: increase of backscatter. White and black areas: unchanged high and low backscatter respectively. d. Detail result of flood areas classification by hierarchical pairing algorithm. RGB = Red Green Blue. S-1 = Sentinel-1.

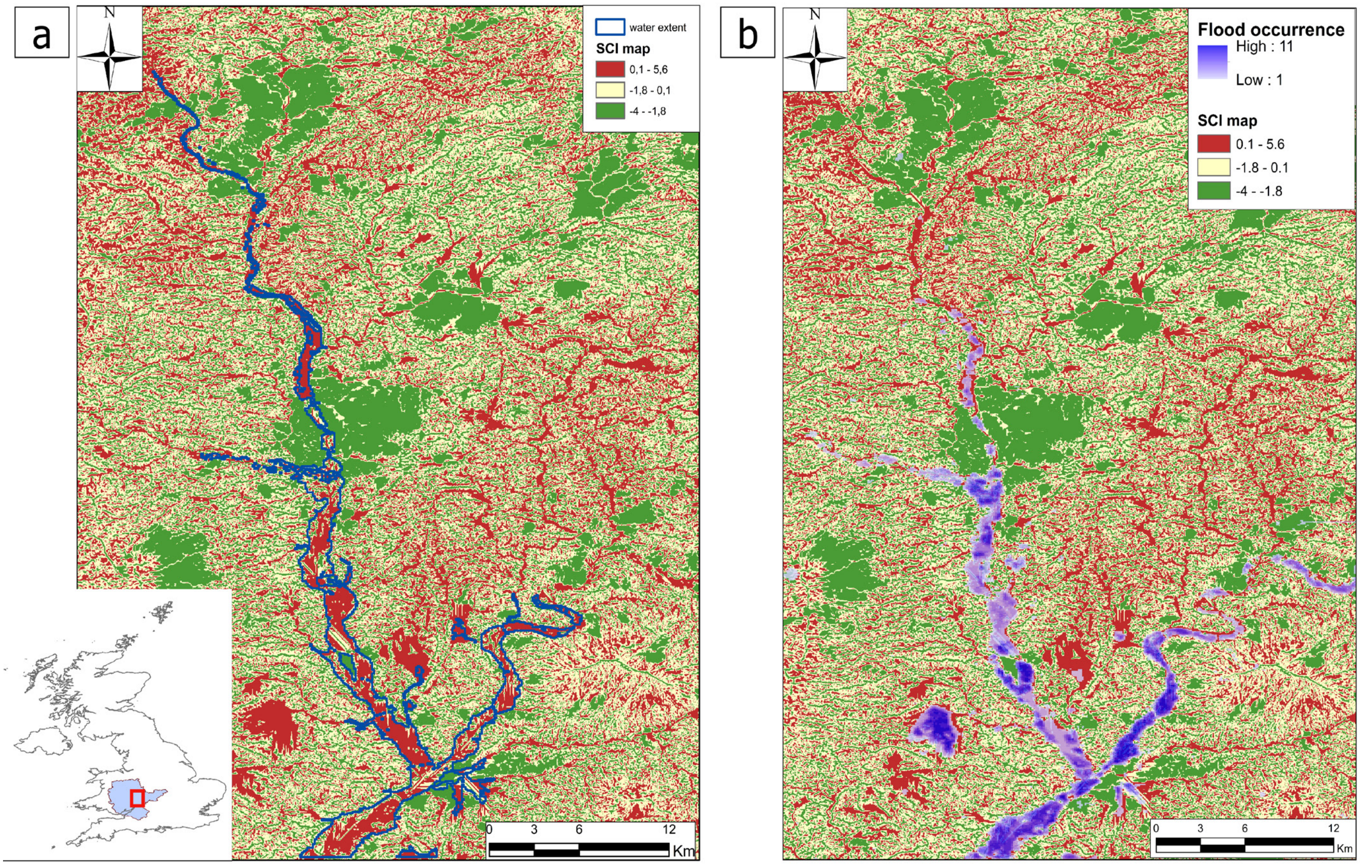

Fig. 2 - a. SCI map with overlaid water extent borders (blue line) relative to the flood event that occurred on July 2007 in study area 2 (red box) of Severn River basin (below). From Zingaro et al., 2020, Fig. 4a (slightly modified). b. SCI map and flood occurrence map relative to the 11 flood events considered (different blue gradient regions). From Zingaro et al., 2020, Fig. 5a. SCI = Sediment flow Connectivity Index.

MAPPING OF FLOOD VEGETATED AREAS

The combination of different typologies of Synthetic Aperture Radar-SAR data (multi-polarization/multi-frequency) and various techniques of image processing is applied to distinguish flooded areas characterized by diverse types of vegetation by taking advantages from different wavelengths (C-band, L-band) and polarizations (Vertical Vertical-VV, Horizontal Horizontal-HH, Horizontal Vertical-HV) of SAR imagery. A dataset composed by 9 SAR images (Sentinel-1, ALOS-2) acquired in Study Area 1 before and during a flood event occurred in January–February 2015, is processed by different methods in four steps. (1) Multi-temporal analysis is applied to Sentinel-1 images by using DAta Fusion by bayesian Network-DAFNE algorithm (D'Addabbo et al., 2018) to analyse flood event evolution. (2) Red Green Blue-RGB composition is applied to pre- and co- event images to identify the backscattering behaviour related to flood event and the differences between C-band and L-band in flood detection. (3) K-means clustering is applied to identify the areas characterized by these backscattering phenomena considering the land cover types (the number of initial clusters, assumed in flood and not flood conditions, is identified by Corine Land Cover). (4) Cluster hierarchical pairing through automatic algorithm is applied to identify the more likelihood number of flood classes by means of an unsupervised clustering approach (Chini et al., 2014).

DETECTION OF HIGH FLOOD OCCURRENCE AREAS

The application of a new geomorphic index, the Sediment flow Connectivity Index (SCI), in a region recurrently flooded is based on an integrated approach for investigating the correlation of fluvial and flood processes. The applicative version of SCI map (Zingaro et al., 2019) obtained in Study Area 2 is compared with 11 available flood maps derived from SAR observations (Giustarini et al., 2016). First, flood map of an extreme event (occurred in 23th July 2007) is overlapped to SCI map in order to evaluate a potential agreement between high connectivity areas and flood region. Secondly, flood occurrence map relative to 11 flood events occurred in 2007-2010, are overlapped to SCI map in order to assess the potential agreement between high connectivity areas and high flood occurrence areas.

MONITORING OF FLOOD EXTENT IN SUB-CATCHMENTS

An innovative integrated methodology is experimented to improve the monitoring of flood extent in fluvial sub-catchments. A probabilistic flood map derived from SAR data (Giustarini et al., 2016), relative to the same extreme event in the selected Study Area 2, is assimilated in 15 flood hazard maps (Return Period from 1 to 1000 years) derived from hydrodynamic model (LISFLOOD-FP, Bates & De Roo, 2000). The assimilation is applied through particle filtering method (Chen at al., 2018) in order to implement satellite observation of flood extent in estimated flood scenarios (Hostache et al., 2018). The integration of satellite and modelling data is performed in 9 spatial units, i.e. micro drainage areas, determined by a sequential processing in Geographic Information System-GIS platform (Magesh et al., 2012). The expected final assimilated map should describe flood inundation by identifying estimated flood extent (from model) actually occurred during the observed (by satellite) event in each sub-catchment.

APPLICATIVE SOLUTION FOR A "GLOBAL INUNDATION RISK"

The application of data integration methodologies and new technologies is experimented in order to develop a solution that provides fundamental information, such as flood inundation exposure, in a simple and smart way. An automated procedure describes and classifies any geographical point of the Italian region (study area 3) in levels of flood inundation exposure, named "global inundation risk" levels, through a weighting procedure applied on different hazard categories. A collection of data is used for hazard characterization and evaluation: flood hazard maps, hydrogeological vulnerability catalogue, topographic and geomorphological features from Digital Elevation Models. Open source data (http://www.sinanet.isprambiente.it/it/sia-ispra, http://avi.gndci.cnr.it/) are applied to obtain a final map of "Global inundation Risk" of Italy.

RESULTS

FLOOD MAPS IN ZAMBEZI RIVER BASIN

The integrated methodology is applied in a region of Zambezi River basin at the confluence of Zambezi-Shire Rivers. Various types of land cover (Fig. 1a) characterize this recurrently flooded area. The multi-temporal flood map (fig.1b) allows us to follow flood event by observing the peak of flood in January 2015 and an assumable steady condition between 3rd and 15th February. RGB combination maps (fig.1c) identify the areas with a different trend in Sentinel-1 and ALOS-2 images in an assumable similar flood condition. Flood areas classification, resulting by the application of the cluster hierarchical pairing (fig.1d), distinguishes flood areas with various land cover types by classifying backscattering values from different frequencies and polarizations. For example, the classification well recognizes floodwater below the canopy in open forest (light blue areas in Fig. 1d) by describing potential double-bounce phenomena more detectable in HH and HV L-band rather than VV (Refice et al., 2020).

COMPARISON OF SCI INDEX MAP AND FLOOD MAPS

The experimental application of SCI index to detect high flood occurrence areas along the channels was executed in a recurrently flood area of Severn River Basin (Fig. 2). The visual comparison of SCI and flood maps shows that (1) water extent of the extreme event (blue line) corresponds to the areas with a higher connectivity (red areas) (Fig. 2a), and (2) recurrently flood areas (with major flood occurrence from light blue to blue in the figure) fall inside high connectivity region (Fig. 2b).

ASSIMILATED FLOOD INUNDATION MAP

A preliminary result is obtained by applying the innovative methodology for flood extent monitoring. Assimilated map (Fig. 3) shows flood inundation occurred during the event distinguishing maximum water extent in each of 9 sub-catchments. Flood extent is associated to distinct scenarios of prevision that might suggest a different trend of event dynamics along the channel during the inundation.

"GLOBAL INUNDATION RISK" MAP OF ITALY

A first "global inundation risk" map of Italy was obtained by applying the applicative solution. This product (Fig. 4) visualizes areas with lower or higher flood exposure

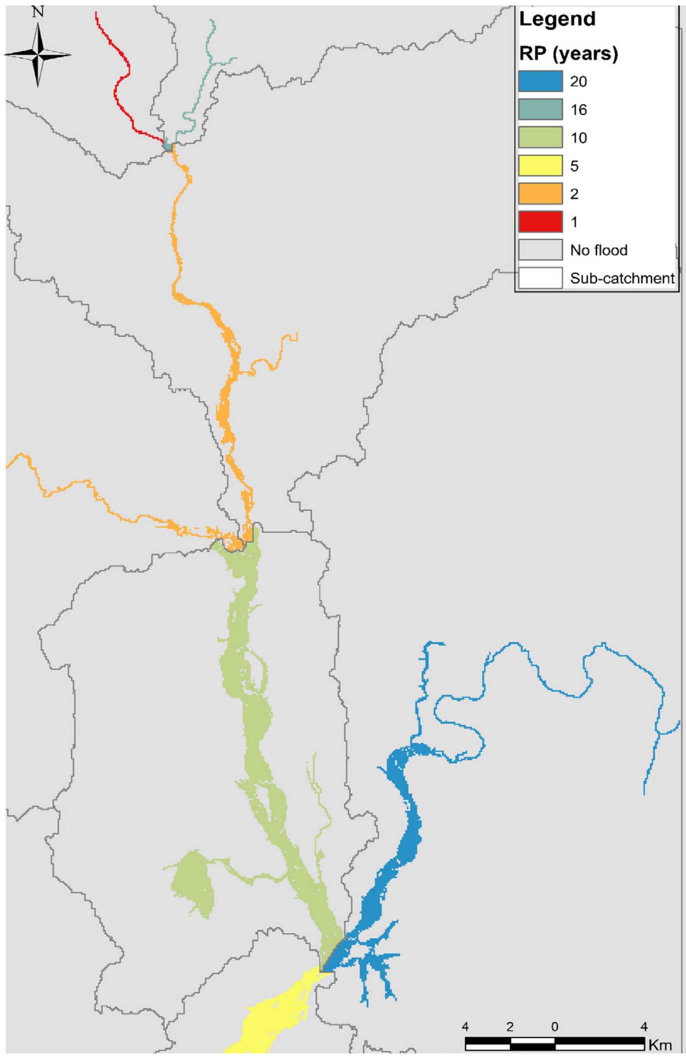

Fig. 3 - Assimilated flood inundation map from assimilation procedure applied in 9 spatial units. RP = Return Periods.

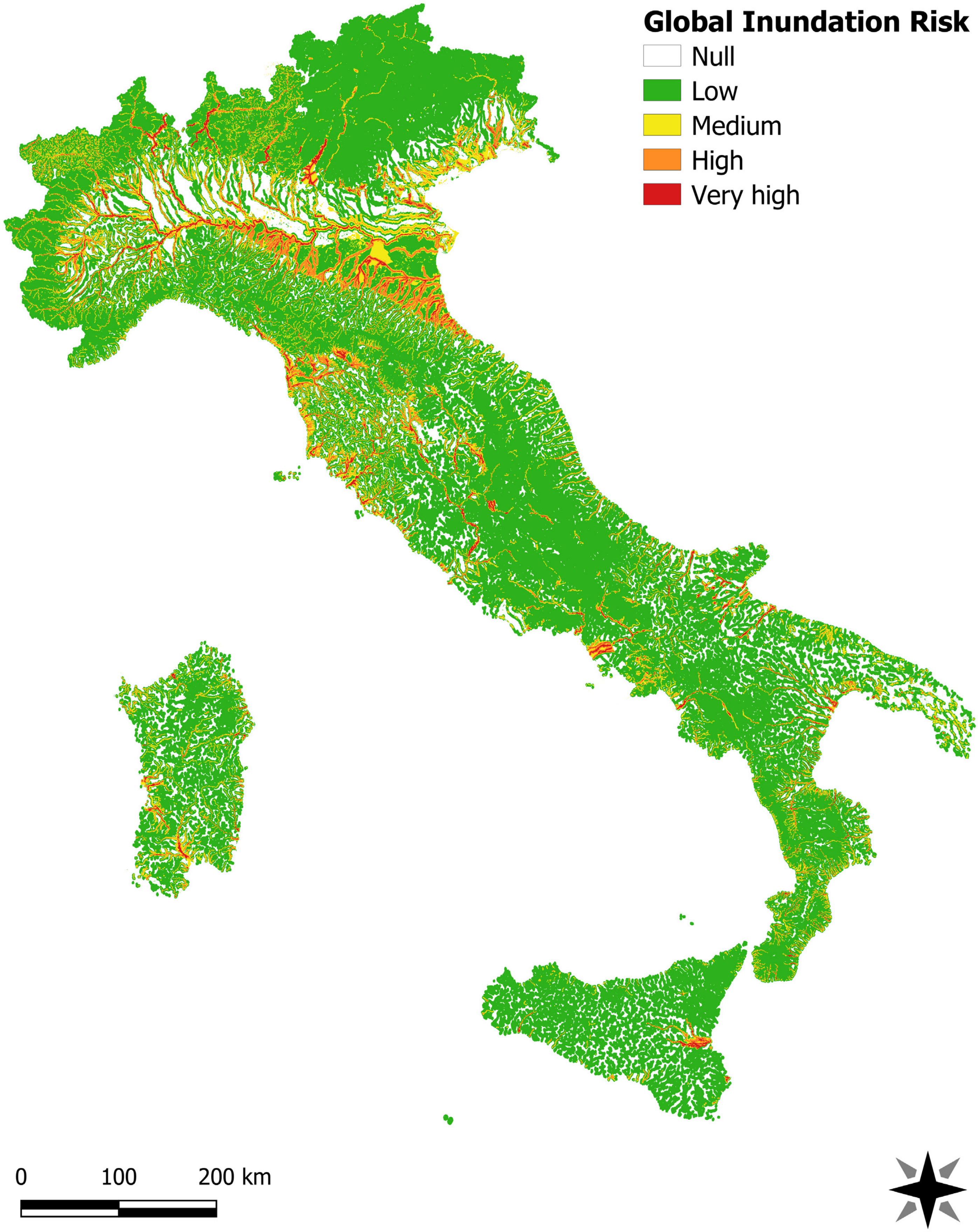

Fig. 4 - Map of "Global Inundation Risk" of Italy (spatial resolution: 20 m).

(from green to red areas, respectively) through five levels of "global risk": null, low, medium, high, very high.

DISCUSSION

Flood event is investigated in the causes and the effects through the application of new techniques and technologies. The combination of different data sources allows developing innovative methodologies and operational systems for flood monitoring, by exploiting the multidisciplinary approach. As the results show, fluvial geomorphology gives the means to understand river behaviour and flood dynamics, satellite remote sensing contributes to observe flood extent at high spatial resolution, and hydrodynamic modelling is a potential tool to simulate expected flood scenarios.

The experimental application of new Sediment flow Connectivity Index (SCI) to detect high flood occurrence areas along the channels confirms the high potential of data combination in river processes investigation and suggests the high value of the geomorphological index in flood monitoring (Zingaro et al., 2020).

The studies applied in the Zambezi River and Severn River demonstrate the advantages offered by SAR data for the observation of water extent over time. In the first case study, the detection of flooded areas improves with the fusion of data (multi-polarization, multi-frequency) by distinguishing the presence of water in relation to land use, vegetation height, soil cover (Hess et al., 1990; Hong & Wdowinski, 2013; Refice et al., 2020). Furthermore, flood event observation can be considered not only as a solution for the definition of open water areas, but also as useful product for the assimilation with modelled data. In fact, in the other case study, the assimilated flood inundation map represents an instrument to observe water dynamics during a flood event by indicating flood effects in spatial units, defined by the distribution of hydrological processes and morphological characteristics in a basin. In the perspective of flood monitoring, a map of improved flood extent with estimated return periods expressed in different sub-catchments, responses to the requirement to manage the various areas of a fluvial basin during a flood event.

The scientific explorations can be translated into operational systems in order to develop solutions able to meet the needs of the society. The "global inundation risk" map of Italy could prove useful for: (1) making available and dynamic the information about flood inundation exposure everywhere in Italy, and not in some restricted zones, (2) expressing flood exposure on a graduated scale of values (levels), and not by just return periods (hazard). These elements meet the need of accessing information that is widespread and spatially continuous and categorized and sorted for phenomenon intensity that are required for improving safeguard activities and preventing the economic loss, for example defining policies for people and goods by insurance companies.

This work constitutes a contribution to develop flood monitoring systems by applying fusion data methodologies in the perspective to give a support for flood risk assessment.

CONCLUSIONS

The present work summarizes the research activities related to a PhD project about the advanced analysis and the integration of remote sensing and *in situ* data for flood monitoring. Fluvial geomorphology, remote sensing and hydrodynamic modelling contribute to examine flood phenomenon and to improve the accuracy of flood hazard assessment by applying new techniques and technologies. The main inferences are:

i. The combination of different data sources and methods is functional for detecting and monitoring flood events;
ii. Scientific exploration gives the means to design solutions for solving practical problems.

Experimentations suggest the need to continue the research in order to deepen first promising results and to overpass some limits emerged during the project.

The present short note is extracted from the thesis of an innovative industrial PhD project, conducted in 2017-2020 years. The activities were cast in the framework of the national operating program for research and innovation (PONRI 2014-2020) and follow the national strategy for smart, sustainable and inclusive growth (smart specialisation strategy, SNSI). The research project was realized by the Department of Earth and GeoEnvironmental Sciences of University of Bari with the cooperation of the Luxembourg Institute of Science and Technology (LIST) in Luxembourg, National Research Council-Institute for Electromagnetic Sensing of the Environment (CNR-IREA) in Bari, and the Italian Planetek-Italia Company in Bari.

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