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Flood risk assessment of environmental pollution hotspots

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ABSTRACT

The potential spread of pollutants stored in environmental hotspots such as wastewater treatment plants, waste handling facilities, contaminated sites, etc., is among the adverse consequences of floods. This aspect has been rarely examined with a risk-based approach, although required by the European legislation. In this study, a method for estimating flood risk caused by environmental hotspots is developed. Risk includes flood hazard, hotspots exposure, and the expected severity of the environmental impacts, obtained as the combination of vulnerability of the surrounding environment and pollution potential of the hotspots. The assessment is performed at catchment scale on a geographical basis, using open data, available from databases of public bodies and environmental agencies. Risk maps obtained by the application of the developed method are produced for the Arno river catchment in Tuscany (central Italy). The area hosts approximately 1750 environmental pollution hotspots among which 5–10% have been classified at high risk.

1. Introduction

Floodplains provide crucial ecosystem services (Schindler et al., 2014), particularly drinking water supply, and often suffer of local anthropic pressures as well as wider driving forces such as climate change (European Environment Agency (EEA), 2016). Most of the cities and their industrial and technological networks have developed near rivers, which offer favorable conditions for development, such as the availability of fertile lands and fresh water, but the cost for such favorable location is an increased exposure to floods (World Meteorological Organization, 2008). Floods may affect critical infrastructures, which can be responsible of soil, surface and groundwater pollution. Among them are wastewater treatment plants (WWTPs), landfills and waste handling facilities (WFs). WFs are susceptible of erosion and leaching behavior, thus are potential emitters of hazardous substances if flooded (Neuhold and Nachtnebel, 2011). Moreover, WWTPs and WFs are technological systems which can be subject to multiple failures of control systems, instruments and electric power-fed machines in case of flood (Krausmann and Baranzini, 2012; Xavier and de Sousa Junior, 2016). This, especially for WWTPs, may lead to treatment restrictions which cause the discharge of effluent with high organic load, or release of chemicals used in the plant. Other important sources of pollution are contaminated sites (CSs), particularly sensitive to inundations because the permanence of floodwater can be responsible of the spread of undesired chemical compounds in the environment. WWTPs and WFs differ from industrial pollution sources since their primary role is to protect the environment and their functioning is strictly regulated and monitored by public environmental protection authorities. CSs are as well under public control since environment authorities watch over reclamation procedures in the best interest of the community. The achievement of a sustainable flood risk management (EU Parliament, 2007b) ensuring a good ecological status of water bodies (European Community, 2000) is promoted by EC legislation and requires an adequate and comprehensive knowledge of pressures and natural hazards. Although not easily monetizable, environmental benefits of flood mitigation strategies should be accounted for, since environmental quality is necessary for human health/wellbeing (Zeleňáková and Zvijáková, 2016). WWTPs, WFs and CS are here defined as environment pollution hotspots (EPHs). Moreover, the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR) promotes the increased awareness toward risk and resilience of the environment as a key priority.

Flood risk is usually defined as the combination of the probability of occurrence of events and the potential consequences on people, environment and anthropic structures. According to this definition,

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risk can be modelled by three components: hazard, exposure and vulnerability. Evaluating possible adverse consequences on the environment of flood-exposed EPHs requires the identification on one hand of the vulnerability of the environment (e.g. land use, surface water quality, aquifer status and use) and of the characteristics of the source of pollution (e.g. eutrophication potential, toxicity etc.) on the other hand. A widely used method for assessing aquifer vulnerability is the DRASTIC model (US EPA, 1987) which allows the evaluation of groundwater susceptibility to pollution through the combination of spatial parameters (e.g. hydraulic conductivity, terrain slope) in GIS environment. The DRASTIC model is usually adopted for contamination risk due to pesticides in agricultural land (Babiker et al., 2005; Bartzas et al., 2015; Neshat et al., 2014) and anthropic pressures (Wang et al., 2012).

Heavy metal and chemical soil contamination has been already reported after major floods (Albering et al., 1999; Euripidou and Murray, 2004; Bird et al., 2005; Bravo et al., 2009; Cunningham, 2005; Krausmann et al., 2011; Cozzani et al., 2010; Lynch et al., 2017). Flooding of landfills represents a recognized environmental risk (Laner et al., 2009; Wang et al., 2012) and flood risk associated with waste disposal has been evaluated in Austria (Neuhold and Nachtnebel, 2011) also using a micro-scale approach for selected case studies (Neuhold, 2013). Parsimonious modelling approaches have also been adopted to simulate substance transport in polder systems for environmental flood risk assessment (Lindenschmidt et al., 2008). However, a macro-scale environmental flood risk assessment comprehensive of various types of EPHs is rarely found in literature (Zeleňáková et al., 2016). Nevertheless, the impacts of natural hazards on technological systems is increasingly recognized as a possibly important external risk source for polluting facilities (Krausmann and Baranzini, 2012). Flood risk assessment methods depend on (i) the scale (e.g. micro-, meso-, macro-scale), (ii) data availability and (iii) scope of the analysis. Macro-scale flood risk assessment (Ward et al., 2013) is carried out at national/regional level possibly including large catchments; examples of meso-scale are district/municipality areas, while micro-scale refers to sub-municipal areas (Apel et al., 2009). The smaller the scale, the higher the need of data accuracy and resolution. Especially for regional studies it is common to have EPHs information only with some indicative data such as plant capacity, but without specific details on hazardous substances (Girgin and Krausmann, 2013). The availability of open data is a crucial aspect for environmental studies and open GIS platforms are becoming increasingly available in EC countries as a consequence of the Directive 2007/2/EC (EU Parliament, 2007a), whose aim is establishing an Infrastructure for Spatial Information in the European Community. Open spatial data sharing and reuse in fact, is seen as the way to foster participation of citizens in political, social and environmental issues and increase transparency of government.

The aim of this work is the identification of potential anthropic sources of pollution at risk of flooding, possibly inducing contamination of soil, surface water and groundwater. The flood risk assessment is carried out at catchment scale, by adopting open data available from public authorities. WWTPs, WFs and CSs are the target environment pollution hotspots, characterized by several parameters used as proxy of their pollution potential. Flood probability is merged with pollution potential of the source and environmental susceptibility. The latter is evaluated through a GIS based approach inspired by DRASTIC model. A vulnerability index is defined and combined with EPHs flood hazard to derive flood risk maps capable of three main features:(i) identifying the EPHs at higher risk of flooding in the catchment to be further analyzed at micro-scale, (ii) providing new insights of potential adverse consequences of flood on the environment to support risk management strategies and (iii) prioritizing local retrofitting interventions. Results are shown for the Arno river catchment in Italy (9116 km^2 of area) where 267 WWTPs, 529 WFs and 947 CSs are present.

2. Materials and methods

2.1. Risk assessment method

A widely accepted definition of risk is expressed by the product of hazard (H), vulnerability (V) and exposure (E) (De León and Carlos, 2006; Kron, 2005):

$$R = HVE \quad (1)$$

where hazard (H) is related to the probability that the event occurs (e.g., event magnitude associated to a specified return period), vulnerability (V) is the predisposition for a given receptor to be adversely affected, exposure (E) refers to the presence (location) of properties or people, area of habitats, and so on in places that could be adversely affected by physical events (Lavell et al., 2012). The product of vulnerability (V) and exposure (E) is the damage. For the evaluation of environmental flood risk, vulnerability is here considered as the combination of harmful potential of pollution source and environmental vulnerability (Fig. 1). In fact, flooded EPHs located in the vicinity of naturally protected areas or close to aquifers used for domestic water supply cause higher impacts than those located in industrial areas.

Exposure (E) analysis is related to the identification of EPHs potentially affected by the flood for assigned recurrence interval scenarios. Objects exposed to flood are usually assigned value 1, while EPHs not exposed are assigned value 0. The vulnerability (V) is disaggregated into factors, each of which is assigned a weight; each factor is characterized by attributes with assigned numerical values representing their relative degrees of importance to vulnerability. Each considered EPH is characterized by specific attributes, associated to the properties of the hotspot itself (e.g. type of waste is a factor for WFs, plant capacity is a factor for WWTPs). Similarly, the environmental vulnerability is classified according to susceptibility factors and their attributes (e.g. land use, chemical status of the water body receptor etc.). Therefore, the vulnerability index (VI_i) for the i-th EPH combines environmental characteristics of the surrounding area and EPH pollution potential. VI_i is defined as follows:

$$VI_i = \sum_{j=1}^{N} (W_j V_j) \quad (2)$$

where N denotes the total number of parameters, and V_j the numerical value of the attribute of the j-th parameter, weighted by its associated weight W_j. The parameters adopted in this study to assess the vulnerability index are shown in Tables 2 and 3. Environmental and EPH attribute values are assigned based on expert judgment; thus the involvement of stakeholders and public bodies is crucial to establish priorities for each case study and local level.

The flood risk assessment returns a classification of EPHs based on a risk index RI_i, calculated as the combination of hazard level (H), exposure (E) and vulnerability VI_i:

$$RI_i = H_i VI_i E_i \quad (3)$$

2.2. GIS layer attribute enrichment

The open data used in this study were available in a variety of formats and stored in different types of databases. The data could