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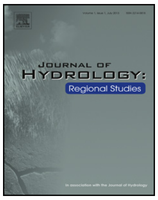

Soil sealing and flood risks in the plains of Emilia-Romagna, Italy

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ABSTRACT

Study region: The plains of Emilia Romagna, Italy.
Study focus: Urban expansion is among the main causes of increase in flood frequency and intensity in small rural catchments in Europe, and our study region is paradigmatic in this respect. We present here a regional screening-level assessment of soil sealing impacts in terms of increased flood peak discharges and flooding volumes on the secondary drainage network of the plains. We estimate flood peak discharges and flooding volumes through a simple kinematic model with runoff coefficients for the land use of 2008 and 1976. Additionally, we calculate an equivalent compensatory flood detention volume that would enable preserving flood peak discharges as prior to soil sealing (principle of "hydraulic invariance"). The proposed approach is simple and readily applicable to any region facing similar issues, for screening-level assessment of flood hazards over an extended stream network.
New hydrological insights for the region: The analysis highlights a significant increase in flood hazards throughout the secondary stream network. The impact. Widespread and relatively uniform, is more apparent in smaller catchments and in the case of more permeable soils. This demands retrofitting of the majority of the drainage network and/or significantly higher costs from flooding damages. The analysis suggests that costs of additional flooding after soil sealing may be higher than those of soil sealing impacts compensation through flood detention (hydraulic invariance).

1. Introduction

Soil sealing is the permanent covering of the land surface by buildings, infrastructures or any impermeable artificial material. It has been identified as a major threat in the Soil Thematic Strategy of the European Commission (European Commission, 2006), both in terms of permanent loss of soil as a resource and for its important impacts on soil functionality. A review by Scalenghe and Ajmone Marsan (2009) summarizes the relevance of soil sealing as an impact pathway of human activities on the environment. The importance of soil sealing in urban areas is perceived as a driver of flood risks in many contexts (see e.g., Pitt, 2008; Malucelli et al., 2014).

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In a recent Staff Working Document of the European Commission, the amount of land take for urban development at EU scale is estimated at about 1000 km^2 per year (European Commission, 2012), causing serious concerns. In the same document, guidelines on best practices are presented based on the concepts of limiting soil sealing, whenever possible; mitigating the impacts on soil and soil functions, where new constructions are unavoidable; or compensating with measures directed to improve soil functionality and environmental services in areas where convenient (e.g., de-sealing sealed surfaces, or rehabilitating degraded areas). The relevance of soil sealing effects on floods has been highlighted in several cases (e.g., Nestroy, 2006; Verbeiren et al., 2013; Du et al., 2015). Recent floods throughout Europe have raised societal concerns around the issue of land take by urban expansion, which can significantly increase peak discharges and inundation volumes especially in smaller catchments with artificial drainage networks. Most of these networks were originally designed for land reclamation in agricultural catchments: as damages to agricultural land induced by floods with high return periods might be acceptable compared to the costs of larger hydraulic works, drainage used to be sized to convey a discharge of relatively short return period.

Among others, the Northern Italian region of Emilia Romagna has assisted to a significant expansion of urban areas over the last four decades.

During flood events occurring regularly in the last 20 years, the artificial drainage network was often loaded with increased discharges due to the significant proportion of land turned from agricultural to urban; at the same time, flooding caused more relevant damages as settlements are typically more vulnerable than simple agricultural land. A paradigmatic event occurred in October 1996 when, following an approximately 100-year return period rainfall of around 200 mm in two days, almost a third of the plains in the region were flooded due to insufficiency of the local drainage networks. This event uncovered how the development of urban areas in the years 1970–2000s had generated massive costs for the retrofitting of the drainage network, and triggered response from planning, accelerating the development of river basin scale flood management plans (e.g., Autorità dei bacini regionali romagnoli, 2001) as prescribed by the Italian legislation of the time, later aligned with the European Floods Directive (European Commission, 2007).

Understanding the distribution and intensity of soil sealing impacts on flood hazards is key to management.

In this paper, we focus on the secondary drainage network in the plains of Emilia Romagna, in most cases made of artificial or highly trained channels, with a catchment area below 100 km^2. Building on previously published work on the impact of soil sealing on flood runoff coefficients (Ungaro et al., 2014), we calculate conventional potential inundation volumes as an indicator of flood risk specifically due to soil sealing by urban land take, without detailed modelling of the stream network, and a complementary indicator given by the equivalent flood detention volumes required to keep peak discharges after land take to the levels prior to land take. These indicators allow understanding the extent, distribution and magnitude of flood hazards arising from soil sealing.

2. Materials and methods

2.1. Study area

Emilia Romagna (latitude 43°50′N–45°00′N; longitude 9°20′E–12°40′E Greenwich, approximately) is a region in Northern Italy with a total area of 22,124 km^2. The main agricultural area, covering slightly more than half of the region (12,000 km^2), is the continuous plain stretching south of the Po river and delimited by the Apennines range on the south and by the Adriatic sea on the east (Fig. 1). Maximum and minimum average annual temperature are 19.3 and 8.2 °C, respectively; mean annual precipitation ranges from 520 to 820 mm. The soils of the area, mainly on quaternary alluvial deposits, are characterised by a high degree of heterogeneity. For this study, we used a map of “soil functional groups” (Guermandi and Tarocco, 2007), where the 237 Soil Typological Units of the 1:50,000 soil map (Regione Emilia-Romagna, 2005) are aggregated according to the top-soil textural family, drainage class, slope, presence of horizons with organic carbon >2.5%, and flooding occurrence (see Supporting information – SI; Guermandi and Tarocco, 2007).

The soils of the Emilia Romagna plain still sustain intensive agricultural productions, mainly consisting of rotating arable crops (cereals, pulses, and forage), orchards and vineyards, even if in the period 1954–2003 agricultural land decreased of about 1200 km^2 mainly due to urbanisation (Di Gennaro et al., 2010). Between 1976 and 2008, the two reference periods considered in this study, urban and industrial areas have increased of about 1000 km^2 (Regione Emilia Romagna, 2011a,b; Malucelli et al., 2014 – see SI). For the implementation of the Water Framework Directive (WFD) 60/2000/EC and the Flood Directive 60/2007/EC, the region belongs to the Po river basin district in its western part, and to the Northern Apennines river basin district in its eastern part. The former is administered by the Po river basin district authority, and the latter directly by Regione Emilia Romagna government with the support of the three River basin authorities of the Reno, the Marecchia and the Romagna (including Lamone, Fiumi Uniti, and Savio) catchments, respectively, see Fig. 1.

2.2. Incremental inundation volumes

For the present analysis, we assume that the drainage network can safely convey a design discharge of 20 years return period, as estimated at the time of design (mostly, pre-World War II) reflecting approximately the level of sealing in 1976. Although a crude simplification, this is a condition representative of the typical hydraulic performance of drainage networks for land reclamation in the region. We may consequently assume that, for a higher return period T and for the level of sealing

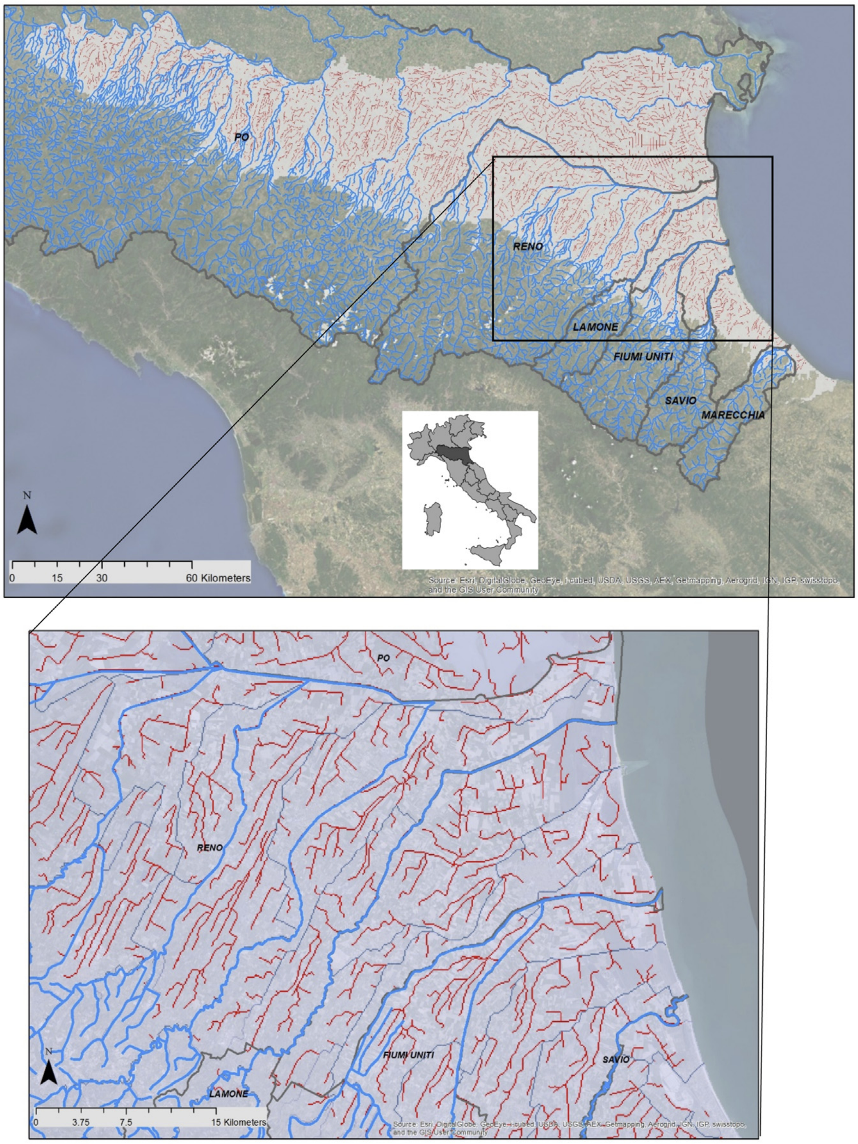


Fig. 1. Above: Map of the study area with labels indicating the drainage basins of the main rivers (Po, Reno, Lamone, Fiumi Uniti, Savio, and Marecchia), streams (blue lines, thinner for artificial canals) and the secondary stream network of the plains (red), on which the study is focused. The inset above shows the position of the Region within Italy. Below: zoom on the plains between Reno and Savio rivers and the coastline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in year y ($y = 1976$ and $y = 2008$), discharges exceeding the conveyance of the stream network, would inundate nearby land. An indicator of the inundation volume potentially flowing out at a generic cross section of the stream network for return period T and year y can be conventionally computed by assuming a triangular hydrograph with time to peak equal to the "time of concentration" of the drainage catchment, t_c, as in the definition sketch of Fig. 2. The potential inundation volume (m^3) is given by:

$$V(T, y) = 3600(Q_{T,y} - Q_{20,1976})t_c\left(1 - \frac{Q_{20,1976}}{Q_{T,y}}\right) \qquad (1)$$

where $Q_{T,y}$ (m^3/s) is the peak discharge of return period T at year y ($y = 1976$ or $y = 2008$). Apparently, for $y = 1976$ and $T = 20$, $V(T,y) = 0$.

This indicator of inundation volume is obviously not a realistic estimate of the actual expected outflow volume first of all because, when computed for all points of the stream network, it does not consider outflows that may occur upstream. More realism would require at least a rudimentary hydraulic model of the actual functioning of the channels and overland flooding, which is not feasible in the scope of this screening-level analysis.

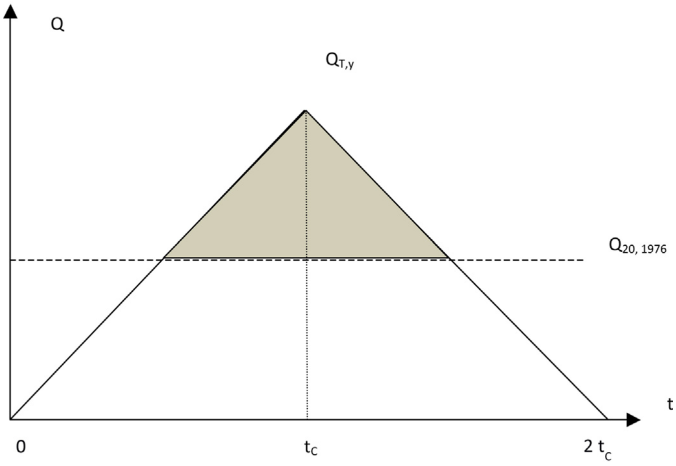


Fig. 2. Definition sketch for the triangular hydrograph model, Q being discharge along the flood event as a function of time t, used in the paper. The shaded area represents flood inundation volume for an event. In the graph, t_c = time of concentration; $Q_{T,y}$ = peak discharge of return period T corresponding to land use at year y and $Q_{20,1976}$ the discharge with return period of 20 years for land use of 1976, assumed to be the conveyance of the stream network.

By assuming that no outflow has occurred upstream and the catchments undergo no hydrologic alteration (such as soil compaction or artificial drainage) other than urban land take, the inundation volumes computed with Eq. (1) at each point of the drainage network are definitely "potential" ones, merely reflecting the relative burden added to the channels by catchment soil sealing.

Having in mind these limitations of the indicator, potential inundation volumes for a return period of 20 years will be greater than zero wherever urban expansion has increased the design discharges in 2008 compared to 1976. Moreover, inundation volumes for floods with return period higher than 20 years will be necessarily greater than 0 both in 1976 and 2008. A typical value of the return period considered for the design of hydraulic protection of urban areas in Emilia Romagna is T = 200 years (e.g., Autorità dei bacini regionali romagnoli, 2003); therefore, it is of interest to evaluate the increase in potential inundation volumes due to floods of this return period, in consequence of urban expansion.

In order to compute the inundation volumes with the procedure described above, we estimate the design discharge $Q_{T,y}$ using the well-known "rational" or "kinematic formula" (see e.g., Maidment, 1993), briefly recalled in the SI, that makes use of a runoff coefficient Φ representing the fraction of the average rainfall during an event, which is converted into surface runoff. While the formula is remarkably simple, estimating an appropriate runoff coefficient entails a number of additional assumptions. In this work, we use the runoff coefficient maps calculated in our previous work (Ungaro et al., 2014, summarized in the SI).

The time of concentration for each catchment is estimated from the upstream flow length assuming a water transfer velocity of 0.5 m/s, a reasonable first-guess value for the area also considering that slopes of the drainage are always in the order to 0.1–1% or less (see e.g., Fig. 3.1 in USDA, 1986). Additional details and an indirect verification of the design discharges used in this study is provided in the SI.

While we consider different degrees of soil sealing in 1976 and 2008, we assume that no change affects precipitation parameters (e.g., due to climate change) or time of concentration (e.g., due to modifications of the network, agricultural drainage or construction of reservoirs). These assumptions are instrumental to isolating the effect of soil sealing from other confounding factors.

2.3. Quantification of flood detention volume requirements to compensate soil sealing

It is generally acknowledged that an increase in runoff due to sealing may be compensated through appropriate flood detention volumes. For instance, Meierdiercks et al. (2010), highlight the importance of runoff detention volumes in driving flood responses in similarly impervious catchments in the US. A few approaches have been proposed for preliminary sizing of detention volumes as required at the stage of land planning (Abt and Grigg, 1978; Donahue and McCuen, 1981; Hong et al., 2006), all entailing some, albeit simplified, hydrological calculations. In this contribution, we refer to the approach of Pistocchi (2001), providing a simple method to calculate the detention volume necessary to compensate a given increment of runoff coefficients in order to keep peak flood discharges unchanged after soil sealing (the so-called "hydraulic invariance"), assuming that the time of concentration is proportional to the hydraulic retention time of a catchment. Based on this approach, after an increase of runoff coefficient from Φ to a value $\Phi' > \Phi$, the initial flood detention capacity W available in a catchment must be increased to a value $W' > W$ given by:

$$\frac{W'}{W} = \left(\frac{\Phi'}{\Phi}\right)^{\frac{1}{1-n(T)}} \tag{2}$$

where $n(T)$ is the exponent of the precipitation depth–duration curve (an extended derivation of the equation is given in the SI). If we refer to small catchments with a time of concentration usually below 1 h, as may be the drainage catchments of new urban developments, we may take $n(T) = 0.48$ for any T (Pistocchi, 2001). This value stems from assuming that rainfall of duration 5′, 15′, and 30′ represent 30%, 60%, and 75%, respectively, of the 60′ duration rainfall with the same return period, as prescribed in the local flood management plans (Autorità dei bacini regionali romagnoli, 2003). The U.S. Weather Bureau (1961) assumes for rainfall duration of 5′, 10′, 15′, and 30′ a percentage of the 60′ rainfall with the same return period of 29%, 45%, 57%, and 79%, respectively, yielding a slightly higher value. A value of $n(T) = 0.48$ may be regarded as a first-guess representative "universal" value for rainfall events of duration of 1 h or less, which are often the most critical for small rural catchments, as discussed in Pistocchi (2001).

We may use Eq. (3) to map the variation of the total storage volume that should be present after soil sealing in the catchment upstream of each point of the drainage network, in order to compensate the increase of runoff coefficients due to soil sealing: the ratio of catchment average runoff coefficients computed through a weighted flow accumulation function (see e.g., Pistocchi, 2014, ch. 7) for 2008 and 1976 yields the required map assuming $n = 0.48$.

In order to turn these volume variations into actual compensatory detention volumes, Pistocchi (2001) suggests to consider a "natural" detention volume of 50 m^3/ha for rural catchments; this value corresponds to soils in the condition of "good pasture" according to ASCE (1969), and is a typical value adopted in engineering design of rural drainage canals in the region of interest. This value is also in line with findings of Sofia et al. (2014), referred to a similar Italian context. Assuming $W = 50$ m^3/ha means considering that the catchment would respond as agricultural land in the initial conditions. In 1976, there were already urban land uses in the catchments; therefore, this assumption provides an upper limit for the storage requirements. The detention volume W^* to be built in an urban development may be thus estimated as:

$$W^* = 50\left(\frac{W'}{W} - 1\right)A \tag{3}$$

where A(ha) is the area of the catchment. With this volume, in principle, we ensure that peak discharges delivered by the development area to the stream network do not increase after soil sealing. The total necessary detention volume W^* in the catchment may be also computed for each point of the drainage network, taking A as the catchment area.

2.4. Limitations from assumptions on the indicators

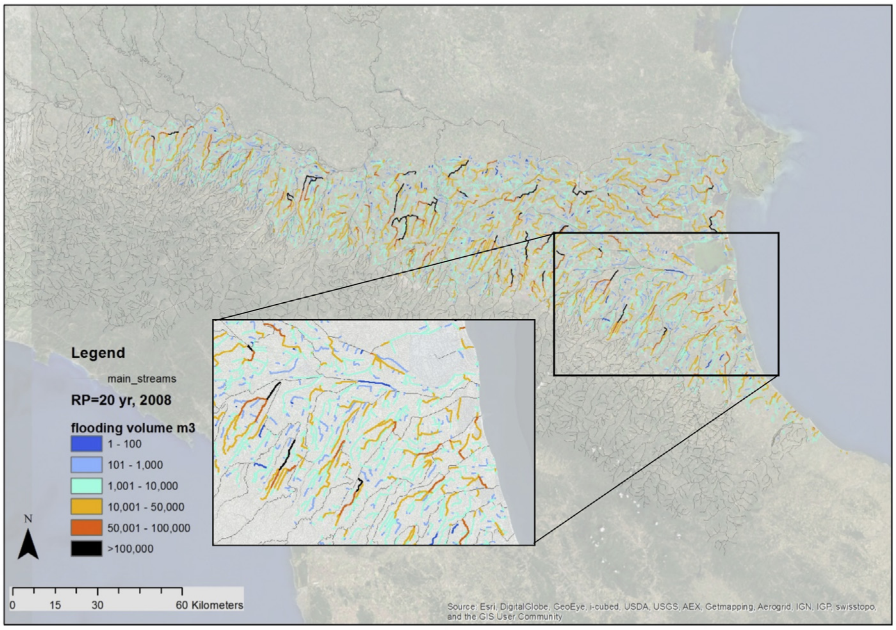
Eqs. (2) and (3) yield mere indicators of the actual volumes of inundation due to soil sealing alone, and the necessary flood detention volumes for compensation, respectively, that should be regarded and used as such. Besides what already pointed out about the potential inundation volumes, limitations that forbid their direct quantitative interpretation include, in Eq. (2), the assumptions of (1) a uniform conveyance of the stream network, corresponding to a design discharge of 20 years return period, and (2) negligible hydrological and hydraulic alterations to the drainage network and the catchments, other than soil sealing, between 1976 and 2008. The latter may be a particularly relevant aspect, as discussed extensively in Sofia et al. (2014).

The detention volume estimated with Eq. (3) is plausible for small catchments, while in the case of larger catchments it is still possible that volumes detained across the drainage area accumulate downstream with a timing that may increase flood peaks; therefore, the required detention volume for the protection of a specific part of the stream network should be evaluated more in depth with dedicated hydrological models. Moreover, the assumption of a uniform value of parameter $n(T)$, irrespective of the return period T, overestimates the volume requirements for catchments with time of concentration significantly longer than 1 h when the precipitation depth–duration curves indicate $n(T) < 0.48$.

Last but not least, several assumptions have been made for the conventional computation of design discharges and initial flood detention capacity. (1) Runoff coefficients for unsealed land have been computed on a conventional basis as discussed in Ungaro et al. (2014); a runoff coefficient equal to 1 as assumed for urban areas (see SI) overemphasizes the effect of soil sealing by neglecting hydrological losses, still present to some extent even during extreme events in urban areas. (2) A uniform velocity used to compute the time of concentration t_c is directly reflected in the values of the latter; shorted or longer t_c yield smaller or larger potential inundation volumes, respectively (an indirect verification of the plausibility of computed design discharges, hence of the runoff coefficients and time of concentration used here, comes from the comparison with design discharges at well-monitored stream gauging stations on the main streams of the region, is presented in the SI). (3) The uniform initial storage volume of 50 m^3/ha assumed for unsealed land is directly reflected in the volume required for hydraulic invariance.

The uncertainty in the indicators due to these assumptions can be appraised only in qualitative terms. Nevertheless, the potential inundation volume indicators computed as discussed above reflect clearly and robustly some fundamental aspects of the regional hydrology, namely:

1. The size of the catchments and their respective time of concentration.
2. The different types of soils present in the catchments, as discussed in Ungaro et al. (2014).
3. The regionalized extreme rainfall parameters $a(T)$ and $n(T)$ for a given return period T.
4. The extent of urban development in the different catchments and on different soils.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Fig. 3. Potential inundation volumes (m^3) for return period of 20 years corresponding to urban expansion in 2008, assuming conveyance equal to peak discharge of return period 20 years in 1976. Results limited to the secondary stream network (drainage area <100 km^2) in the plains.

Table 1
Percentages and lengths of the stream network of the study region affected by different potential inundation volumes for a return period of 20 years after urban expansion.

Volume (m^3)	(%) Of the secondary drainage network	Length (km)
<100	12.00%	895
100–1000	13.3%	994
1000–10,000	44.1%	3297
10,000–50,000	23.7%	1774
50,000–100,000	4.3%	318
>100,000	2.6%	194

Different assumptions would yield different absolute values of the indicators, but would leave ranking of hazards, as well as the comparison of the 1976 and 2008 scenarios, largely unaffected.

3. Results

3.1. Inundation volumes and drainage network retrofitting

Fig. 3 shows the potential inundation volumes for a return period of 20 years, corresponding to urban expansion as of 2008. These volumes are indicators of the demand for drainage network retrofitting to ensure it is brought back to conveyance for a return period of 20 years after urban expansion. The one of retrofitting is the most immediate cost and the minimum requirement in order to keep land exposed to the same flood hazards existing before land take.

The distribution of excess flooding volumes highlights those areas where urban expansion has been most significant. The whole drainage network appears to be affected, with its majority having predicted inundation volumes of the order of thousands to tens of thousands m^3, and some 3% even above 100,000 m^3 (Table 1), classifying many portions of the area at risk of flooding for a return period of 20 years due to soil sealing. Although, flooding volumes are not very large in absolute terms, they are sufficient to fill depressions, encroach underground or ground-level facilities and, sometimes, provoke casualties. This implies a need of retrofitting of some 5000 km of the drainage network in order to ensure safety for a 20-year return period flood. Actually, during the last 20 years, the artificial and secondary drainage network has generally undergone relevant and generalized retrofitting works in the region.

In the SI, we present maps of potential inundation volumes for a return period of 200 years referred to the condition in 1976, while in Fig. 4, we show the increments of volumes after urban expansion as of 2008. While potential flooding volumes in 1976 tend to be rather uniformly distributed across the network (see SI), the highest increases in potential inundation volumes correspond to the most relevant urban expansions (see Fig. SI-1), consistently with our assumptions. In the 1976 scenario, the vast majority of the network has a 200-year return period potential inundation volume of 10,000–100,000 m^3,

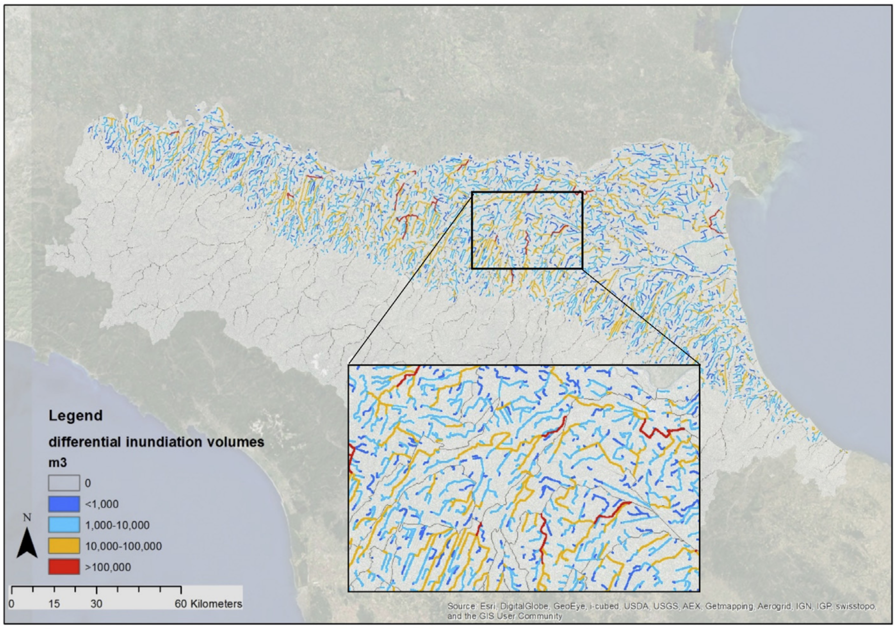


Fig. 4. Potential inundation volume increments estimated for 2008, m^3. Results limited to the secondary stream network (drainage area <100 km2) in the plains.

Table 2
(A) Percentage and total length of the stream network of the study region affected by different volumes of flooding for return period of 200 years, before and after urban expansion; (B) percentage of the stream network of the study region affected by different incremental flooding volumes for return period of 200 years after urban expansion.

(A) Inundation volumes (m^3)	(%) Of network (1976)	Length (km) (1976)	(%) Of network (2008)	Length (km) (2008)	Differential length (km)
0–10,000	2.7%	199	2.3%	175	−23
10,000–100,000	66.9%	5002	65.1%	4867	−135
100,000–500,000	23.5%	1756	24.9%	1861	105
>500,000	6.4%	479	7.3%	545	66
(B) Differential inundation volumes (m3), 1976 to 2008			% Of network		
<1000			21.0%		
1000–10,000			51.0%		
10,000–100,000			26.0%		
>100,000			2.0%		

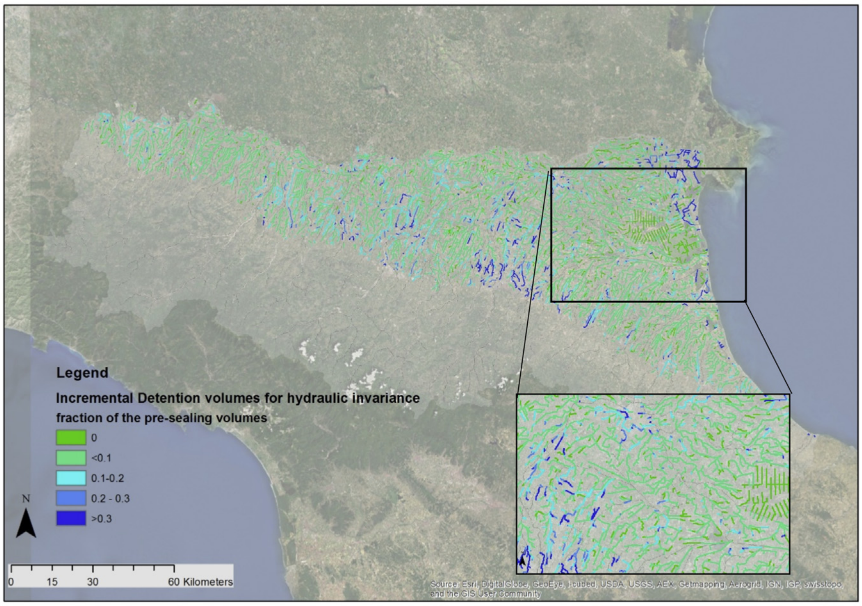
but for about a third of the network this value is above 100,000 m^3 (Table 2). Change in these figures is not dramatic in the 2008 scenario, yet worsening the overall conditions with some 170 additional km of the network with more than 100,000 m^3 potential inundation volumes (Table 2). Table 2 also shows that about 80% of the network is subject to increments in potential inundation volumes of 1000 m^3 or more, with 2% showing increments larger than 100,000 m^3. Although not necessarily very high, these increments in potential inundation volumes may indicate locally severely increased risks.

3.2. Detention volumes to compensate soil sealing

Fig. 5 shows the incremental detention volumes required to compensate soil sealing in 2008, evaluated using Eq. (3). In the catchments where land take is more pronounced, the necessary increments of detention volumes can be 30% or more of the existing volume. The same figure presents these incremental detention volumes in terms of detention volumes W^* (Eq. (3)) to be built on land parcels subject to urban development in order to compensate for the increase of runoff coefficients, under the above mentioned assumptions. While more than 80% of the stream network requires detention volumes of less than 1000 cubic meters, around 15% of it requires volumes up to 100,000 cubic meters and a small part even more than 100,000 (Table 3).

The most apparent impacts are in smaller catchments, where urban land take covers a larger share of the drainage area, and on soils with lower unsealed runoff coefficient.

A comparison of compensation volumes (Table 3) with additional potential inundation volumes for return periods of 20 years (Table 1) and 200 years (Table 2) is shown in Fig. 6. Compensation volumes required for about 80% of the drainage



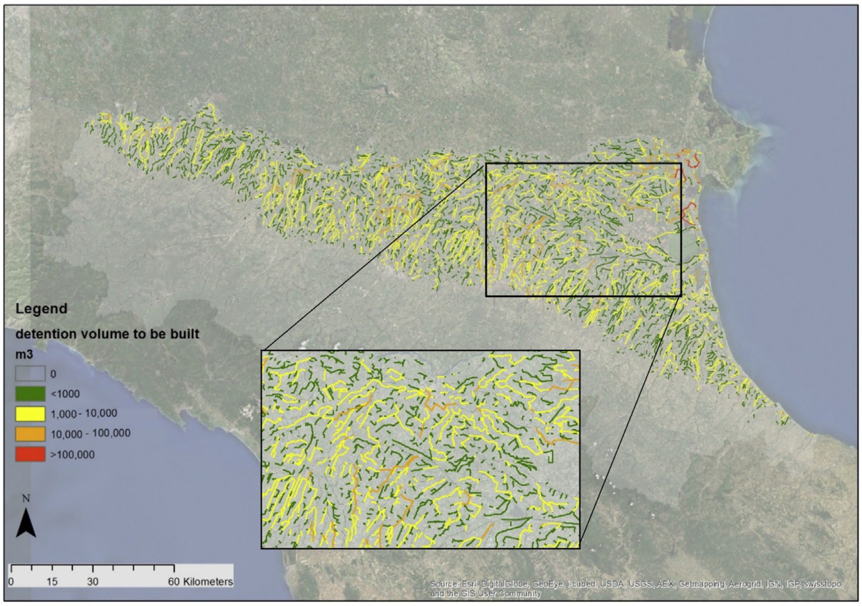


Fig. 5. Above: Incremental detention volume required for hydraulic invariance at catchment level (–), for runoff coefficients with 200 years return period. Below: volume to be built in order to ensure the hydraulic invariance of urban expansion. Results limited to the secondary stream network (drainage area <100 km2) in the plains.

Table 3
Percentages and length of the stream network of the study region affected by different levels of incremental flooding for return period of 200 years after urban expansion.

Hydraulic invariance volume (m^3)	(%) Of the drainage network	Length (km)
<1000	83.8%	6264
1000–10,000	6.2%	465
10,000–100,000	8.9%	667
>100000	1.0%	76

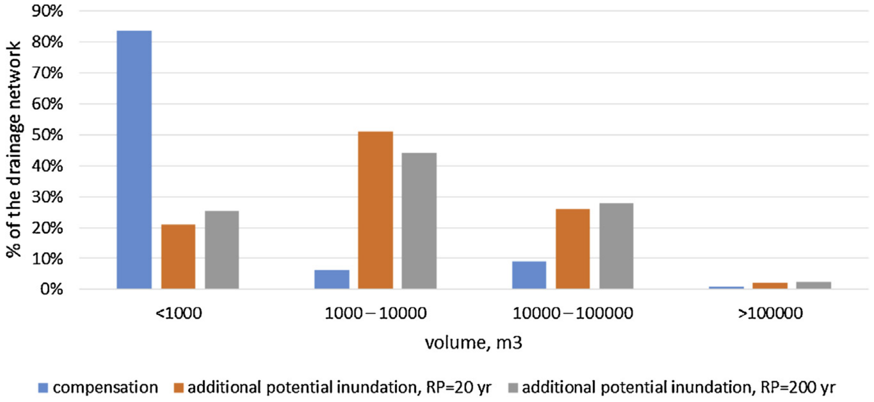


Fig. 6. Frequency distribution of volume indicators over the drainage network.

network are below 1000 m^3. Potential inundation volumes are, on the contrary, above 1000 m^3 for about 80% of the drainage network.

4. Discussion

We have stressed how potential inundation volumes are not reliable as for the actual location of inundations mainly because they neglect outflows occurring upstream. However, we may argue that estimated volumes during one specific outflow are a plausible, albeit conventional, quantification of the overflowing volume. Larger inundation volumes may mean broader extent of flooded areas, and/or longer persistence of flooding after the event, although both are critically controlled by local topography and drainage. The assessment of the actual impacts of these incremental flooding volumes obviously requires site-specific overland flood propagation models, and is beyond the scope of this work. It has been generally observed that urban expansion not only induces more severe flood hazards, but also increases the value of goods exposed to flooding, hence potential damages, although flooding may substantially damage agricultural land as well. In urban contexts, flood damages may be evaluated as a first approximation in the range of 10^2–10^3 euro per m^2 of flooded area (e.g., Messner et al., 2007; Jongman et al., 2012), and we may refer to these figures as a first approximation to value 1 m^3 of inundation volume. Costs of compensation volumes can be estimated from construction and opportunity costs of land allocated to flood detention, and may be estimated in the order of 10^2 euro/m^3, with decreasing marginal costs with increasing volumes (see e.g., Brown and Schueler, 1997), possibly lower than the cost of urban flooding.

In those parts of the drainage network more affected by soil sealing, we may expect higher demand for protection of goods exposed to floods, mainly by retrofitting of the channel conveyance, which may transfer risks downstream, i.e., generally towards those parts of the stream network where we already expect higher potential for inundation. Therefore, although volume indicators forbid a full-blown comparison in terms of actual costs of flood detention and additional flooding, we may argue that compensation of soil sealing may be a cost-effective solution in large parts of the stream network.

The capacity of the design conveyance of the drainage network should also be a community service that cannot be expanded beyond reasonable extents without huge costs, and therefore, it may be assimilated to a limited commodity. Any land use change resulting in increased flood discharges would use drainage capacity initially allocated to other land, eventually exposing areas downstream to more severe inundations, a typical case of “tragedy of the commons” as first discussed in Hardin (1968). The flood detention volumes to compensate soil sealing may represent a “payment” to offset the overuse of this service. In the period between 1976 and 2008, no provisions existed to charge these costs to land development, hence the community paid either through retrofitting of the drainage network (which actually occurred) or through suffering higher losses during floods. Provisions putting the compensatory volume directly in relationship with the extent/intensity of soil sealing would then conform to a “consumer pays” sustainability principle (Pistocchi and Zani, 2004).

5. Conclusions

It is commonly acknowledged that land use change associated to land take and soil sealing, along with other drivers such as climate change and land management, may increase flood risks. This is particularly true in the plains, where artificial hydraulic networks have been planned in the past for agricultural land reclamation: in such circumstances, ditches and canals are typically designed to support runoff from natural and agricultural soil, and the impact of soil sealing may be quantitatively very relevant, although it is rarely evaluated in practice.

We have characterized the effects of soil sealing due to urban land take in Emilia Romagna through simple indicators of inundation volumes and required compensatory volumes for flood detention. Soil sealing in Emilia Romagna yields a widespread and relatively uniform increase in flood hazards, demanding drainage network retrofitting and/or significantly higher costs from flooding damages, which might have been offset in a cost-effective way, through appropriate compensatory measures including constructed detention volumes.

In-catchment flood detention measures have long been advocated (see e.g., Böhm et al., 2004) in the context of a strategic framework for catchment-scale spatial planning, and indicated as an effective solution to urban flooding (e.g., Miguez et al., 2014), although their planning and design may require a system approach in order to ensure optimal performance and avoid drawbacks (e.g., Ravazzani et al., 2014; Ding and Wang, 2012; McEnery and Morris, 2012; Del Giudice et al., 2014a,b). Flood detention strategies contribute to adaptive urban flood management (e.g., Maharjan et al., 2009). A variety of solutions (see e.g., http://www.susdrain.org; Brown et al., 2010a,b) addressing floods together with diffuse urban pollution, reduction of groundwater recharge and other hydrological impacts, have been proposed in action frameworks such as low impact development (LID – see USEPA, 2000) and sustainable urban drainage systems (SuDS – see CIRIA, 2007), that may contribute to urban resilience (Lamond et al., 2015).

An obligation for land developers to preserve peak discharges from urbanized areas to the values corresponding to pre-existing agricultural conditions through adequate flood detention (the “hydraulic invariance” principle), has been introduced by the flood management plans in Emilia Romagna in the early 2000s. A regulatory requirement of minimum flood detention volumes, based on Eq. (3), is imposed to any land use change entailing soil sealing, irrespective of the extent of land affected. In this way, the effects of soil sealing on floods may be minimized with costs entirely paid by the developers, with no extra cost on the collectivity (Pistocchi, 2001; Pistocchi and Zani, 2004). This provision is expected to stimulate planners and designers to limit the extent of soil sealing to a minimum in order to reduce the costs and practical implementation constraints of detention volumes (Dall’Ara and Pistocchi, 2002). A directive containing specific technical guidance has been issued (Autorità dei bacini regionali romagnoli, 2003; Ferrucci and Pistocchi, 2006), which is summarized in the SI.

Detention volumes are also a practical form in which to express the value of soil regulating ecosystem services (in the sense of Daily, 1997; MEA, 2005) with respect to floods, in that they are easily quantifiable and can be valued on the basis of their construction costs and the value of land to allocate. Broccoli et al. (2008) illustrate how compensatory flood detention volumes may be interpreted as a “flood hazard footprint” of urban expansion, and is suitable for prior assessment and posterior monitoring of spatial planning in strategic environmental assessment frameworks as discussed, e.g., in Helbron et al. (2011).

The proposed indicators, of which the limitations have been extensively discussed above, allow screening the regional impact of soil sealing on the drainage network before implementing in-depth hydrological and hydraulic modelling. Screening level analysis may be necessary where the secondary drainage networks in semi-rural catchments is capillary, the relevance of local flooding may be high, and detailed assessment cannot be conducted systematically. Data requirements for the proposed method include design precipitation, information on the typical return period of design discharge in the drainage network, a conventional, accepted engineering estimate of the runoff coefficient for unsealed soil, and a map of areas potentially or actually sealed. Such maps are increasingly available up to the global scale (e.g., Elvidge et al., 2007). This type of analysis allows ranking the drainage network by impact of soil sealing, and can be applied at regional scale e.g., in the development of flood management plans as required by legislation in Europe and elsewhere.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.06.021.

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