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REVIEW ARTICLE

Heat waves and floods in urban areas: a policy-oriented review of ecosystem services

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Abstract Urbanisation is increasing and today more than a half of the world's population lives in urban areas. Cities, especially those where urbanisation is un-planned or poorly planned, are increasingly vulnerable to hydro-meteorological hazards such as heat waves and floods. Urban areas tend to degrade the environment, fragmenting and isolating ecosystems, compromising their capacity to provide services. The regulating role of ecosystems in buffering hydro-meteorological hazards and reducing urban vulnerability has not received adequate policy attention until now. Whereas there is a wide body of studies in the specialised biological and ecological literature about particular urban ecosystem features and the impacts of hazards upon people and infrastructures, there is no policy-driven overview looking holistically at the ways in which ecosystem features can be managed by cities to reduce their vulnerability to hazards. Using heat waves and floods as examples, this review article identifies the aggravating factors related to urbanisation, the various regulating ecosystem services that buffer cities from hydro-meteorological impacts as well as the impacts of the hazards on the ecosystem. The review also assesses how different cities have attempted to manage related ecosystem services and draws policy-relevant conclusions.

Keywords Heat waves · Floods · Ecosystem services · Urban areas · Inland water systems · Environmental vulnerability

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Introduction

Nowadays, more than 50% of people live in urban areas with some 3.5 billion people having settled in cities throughout the world (UNFPA 2009). This urbanisation trend continues today and is likely to continue in the coming decades (UNFPA 2007). As a consequence, large changes in exposure to natural hazards and vulnerability of social-ecological systems are taking place in urban areas. At the local and regional levels, consumption of natural assets and disruption of ecosystems[1] by cities have contributed to the modification of the surrounding environment. Urban development fragments, isolates and degrades natural habitats and disrupts hydrological systems (Alberti 2005). The occupation of floodplains, land conversion, deforestation and loss of ecosystems are anthropogenic factors that contribute to the loss of buffering capacity of ecosystems to hazards. For instance, the impairment of soil functions in urban areas causes the loss of water permeability (i.e. soil sealing), which increases the impacts of

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[1] Ecosystems are the dynamic complexes of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit, including humans (MA 2005, p. 27).

potential floods and the likelihood of urban floods. Besides this, ecosystems can also be affected by hazards that can be an important determinant of vulnerability when communities have high dependencies on specific ecosystem services in and around cities. Extreme, large-scale weather events are likely to trigger ecosystem level disturbances, which may affect the organisation (species composition and diversity) and the functional attributes of ecosystems (Parmesan et al. 2000). Overall, ecological effects of extreme events have been identified as one of the main gaps of knowledge in community ecology (Agrawal et al. 2007).

While there is growing literature on climate change and vulnerability assessment (Adger 1999; Handmer et al. 1999; O'Brien et al. 2004; Füssel and Klein 2006), comparatively little of it concerns cities (Kallis 2008) and even fewer address the importance of urban ecosystem services (Niemelä et al. 2010). There is extended literature on ecosystem services,[2] classification and valuation (Costanza et al. 1997; de-Groot et al. 2002; MA 2005; Fisher et al. 2009), but likewise little of it focuses on the contribution of buffering hydro-meteorological hazards,[3] and much less in cities. This gap is covered by the present review. Our starting point is that there is a large volume of relevant material in specialised literatures, not least ecology, about particular components of the urban ecosystem, but no overarching interdisciplinary and policy-oriented synthesis targeting disaster risk reduction. To ground our analysis we focus on two important hazards, especially for European cities: heat waves and floods.

Section 2 presents the conceptual framework we used for the review. Section 3 discusses concepts related to ecosystem services and urban systems. Sections 4 and 5 review heat waves and floods, respectively. Both sections address the following components of the framework presented in Fig. 1: a description of the hydro-meteorological hazard, the aggravating factors related to urbanisation, the regulating services (e.g. climate regulation, air quality regulation and water regulation) and the impacts of the hazard on the ecosystem. Section 5 reviews related policy initiatives for the protection of urban ecosystem services. The review ends with a concluding discussion and policy recommendations (Sect. 6).

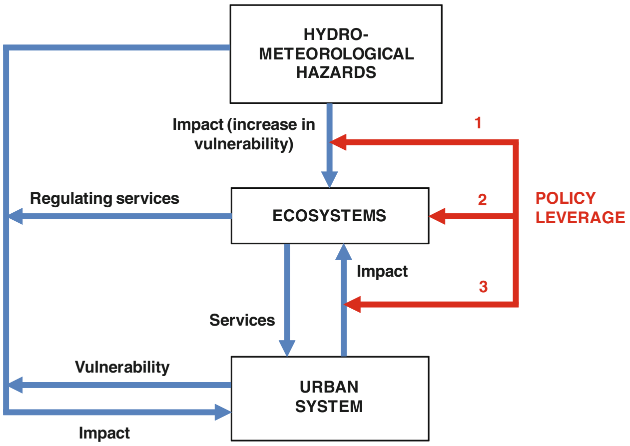

Fig. 1 Conceptual framework highlighting the relationships between hydro-meteorological hazards, ecosystems and urban systems

Conceptual framework

Figure 1 provides a conceptual framework for understanding the relationships between urban systems, ecosystems and hydro-meteorological hazards. While we recognise more integrated definitions of urban ecosystems that include both human and non-human elements in their inter-relation (e.g. Pickett et al. 2001), for the sake of this analysis we maintain a distinction between the human ("urban systems") and ecosystem components. As Fig. 1 indicates, urban areas are vulnerable to hydro-meteorological hazards but ecosystems offer services that can buffer these potential impacts. However, urbanisation as a process erodes these ecosystem services, as do hazard impacts, especially in a context of climate change and intensifying extremes, as indicated in Fig. 1. Urbanisation fragments ecosystems, which diminishes their regulating capacity and increases the vulnerability of urban areas themselves. As shown in Fig. 1, we are also interested in the vulnerability of ecosystems to hazards, defined in relation to the human component, i.e. their capacity to withstand stresses and maintain important regulating and other services. The vulnerability of the urban system derives therefore from the effect of the impacts of the hydro-meteorological hazard on the ecosystem and on the urban system combined with the potential role of regulating services. It is possible to act in different ways to reduce this vulnerability. Conventionally policy has focussed on the urban system component in terms of adaptation policies seeking to reduce the vulnerability of infrastructures or particular segments of the population to hydro-meteorological hazards. This article shifts attention instead to policies that can act on different leverages, such as urban ecosystem restoration and preservation by protecting ecosystems themselves from hazards directly (arrow 1 in

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[2] Ecosystem services are the benefits people obtain from the ecosystem (MA 2005, p. 27).

[3] Hydro-meteorological hazards are processes or phenomena of atmospheric, hydrological or oceanographic nature that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR 2009, p. 18).

Fig. 1), ecosystems restoration and preservation (arrow 2) or indirectly by reducing urbanisation pressures (arrow 3).

Urban areas and ecosystem services

An urban area is defined as "a set of infrastructures, other structures, and buildings that create an environment to serve a population living within a relative small and confined geographic area" (Albala-Bertrand 2003, p. 75). Cities can be additionally defined as settlements that are permanent. The definition of urban areas adopted in national census varies from country to country. Three main classifications of localities as urban can be identified according to: (1) the size of the population (e.g. civic district which is in general greater than 2,000, 2,500 or 5,000 inhabitants); (2) the proportion of population of a civic district engaged in agriculture and the predominance of non-agricultural workers; and (3) administrative, legal criteria (e.g. type of local government) (2007 United Nations Demographic Yearbook). Delimitating urban areas, from a multidisciplinary perspective, is not a straightforward task (Pelling 2003). The city can be considered as a single ecosystem or composed of individual ecosystems: all natural green and blue areas in the city, including street trees and ponds; seven "natural ecosystems" are identified: street trees, lawns/parks, urban forests, cultivated land, wetlands lakes/sea and streams (Bolund and Hunhammar 1999). These ecosystems provide a variety of services including climate regulation, air purification, water regulation and carbon dioxide (CO_2) sequestration. For instance, urban green areas can buffer extreme events such as heat waves and floods by reducing temperatures, increasing ventilation, storing water and reducing run-off (EEA 2010b). The Millennium Ecosystem Assessment (MA) has identified the following classes of ecosystem services: "provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits" (MA 2005, p. 27). The supply of these services are the result of the functioning of ecosystems, representing the products of processes that occur within every ecosystem and, because the processes depend on organisms and the organisms are linked by their interactions, the services themselves are also linked (Fitter et al. 2010). For the sake of this review we focus mainly on regulating services and the multiple benefits they provide for the buffering of heat waves and floods in urban areas. Of all ecosystem services, regulating services are amongst the least investigated and assessed, and regulating service indicators are weaker (i.e. low ability to convey information and data availability) overall than provisioning service indicators (Layke 2009). The analysis is based on the classification of ecosystem services proposed by the MA and the relevant services for each hazard have been identified. For heat waves we considered: air quality regulation and climate regulations, while for floods we analysed water regulation.

Heat waves

Heat waves as a hazard

Heat waves are extreme events associated with particularly hot sustained temperatures able to produce notable impacts on human mortality and morbidity, regional economies and ecosystems (Koppe et al. 2004; Meehl and Tebaldi 2004). In Europe, heat waves have been the most prominent hazard with regards to human fatalities in the last 10 years (EEA 2010a). One well-documented example is the European 2003 heat wave when more than 70,000 excess deaths were reported during the summer (EEA 2010a) and 15,000 excess deaths in France alone (Fouillet et al. 2006). A large precipitation deficit during spring 2003 contributed to a rapid loss of soil moisture (Ciais et al. 2005; Zaitchik et al. 2006; Fischer et al. 2007). As a result, the summer 2003 was by far the hottest since 1500 AD in Europe (Luterbacher et al. 2004), and it seems that heat waves will become more intense, longer lasting and/or more frequent in future warmer climates (Meehl and Tebaldi 2004; Luber and McGeehin 2008).

Urbanisation as an aggravating factor

In urban areas, the impacts of heat waves are aggravated and the vulnerability of ecosystems and urban communities are increased (see Fig. 1). Urban development modifies land surface, leading to the creation of distinct urban climates (Grimmond et al. 2004). Urbanisation has quickly transformed ecosystems to infrastructures and buildings that increase thermal-storage capacity (Luber and McGeehin 2008). Built up and impervious surfaces are stronger absorbers and the radiation is then slowly re-emitted as long-wave radiation that is responsible of warming up the boundary layer of the atmosphere within the urban canopy layer (Oke 1988), producing the so called "Urban Heat Island" (UHI) effect. The UHI effect concerns the magnitude of the difference in temperature between cities and their surrounding rural regions and the temperature difference increases with the number of inhabitants and the building density: in Europe, the maximum UHI goes from 2 to 12°C (Koppe et al. 2004). Due to this effect, the highest morbidity and mortality associated with extreme heat appear to occur in cities (Clarke 1972). Harlan et al. (2006) examined the relation among the microclimate of urban neighbourhoods, population characteristics, thermal environments that regulate microclimates and the resources people have to cope with climate conditions in Phoenix, AZ. Neighbourhoods with few open and green spaces, which have been proven to have cooling functions, contribute to increasing the impacts of heat in cities. Heat waves' mortality rates, neighbourhoods' environmental quality and population characteristics are thus spatially correlated (Harlan et al. 2006).

Climate regulation

As mentioned, temperatures in cities are higher than in the surroundings, which cause higher impacts of extreme heat events. Ecosystems in urban areas contribute to reducing the UHI effect (Bolund and Hunhammar 1999). However, urban forests, a common term to characterise all of the vegetation of an urban region (McPherson et al. 1994), play a particularly important role in regulating climate, energy and water between the land surface and the atmosphere (Zaitchik et al. 2006). According to various authors, greening can cool the environment at least at the local scale (Oke 1989; Akbari et al. 2001; Bowler et al. 2010), providing a climate-regulating service that can buffer the impacts of heat waves. This is because plants and trees regulate their foliage temperature by evapo-transpiration, leading to a reduction of the air temperature. In addition, green vegetation absorbs up to 90% of the photosynthetically active radiation while reflecting up to 50% of the near infrared radiation (Braun and Herold 2003), thus absorbing less heat than built infrastructures. The size of the green area contributes to the magnitude of the cooling effect, although it is not clear if there is a minimum size threshold or if there is a simple linear relationship between these two factors: on average an urban park would be around 1°C cooler than a non-green site (Bowler et al. 2010). Gomez et al. (1998) observed that, in green areas, there was a drop of 2.5°C with respect to the city of Valencia (Spain) maximum temperature. Wong and Yu (2005) observed a maximum difference of 4.01°C between well planted area and the central business district area of Singapore, while according to Hamada and Ohta (2010) the temperature difference between urban and green areas in Nagoya (Japan) was large in summer and small in winter. The maximum air temperature difference was 1.9°C in July 2007, and the minimum was −0.3°C in March 2004. Renaud and Rebetez (2009) compared open-site and below-canopy climatic conditions from 14 different sites in Switzerland during the 11-day August 2003 heat wave. Maximum temperatures were cooler under the canopy and, the warmer the temperature, the stronger the impact of the forest. For maximum temperature, the difference was higher in deciduous and mixed forests compared to coniferous forests. For minimum temperature, in contrast, the discrepancy was higher in coniferous forests (Renaud and Rebetez 2009). Similarly it is worth noting that, during heat wave days, the increase in sensible heat flux is initially much larger over forests than over grasslands (Teuling et al. 2010). In the long term, however, grasslands become the main heat source due to the fact that elevated evaporative cooling accelerates soil moisture depletion (Teuling et al. 2010).

According to Alexandri and Jones (2008), although parks manage to lower temperatures within their vicinity, they are incapable of significantly cool the surrounding areas where people live. Therefore, the authors suggest that it would be more effective to place vegetation within the built space of the urban fabric; thus raised urban temperatures can decrease within the human habitats themselves and not only in the detached spaces of parks. For single trees, evapotranspiration and tree shading are important control measures in heat-island mitigation in Tel-Aviv (Shashua-Bar and Hoffman 2003). According to these researchers, the cooling effect depends mainly on the amount and extent of the partial shaded area. For instance in Athens, during a short exceptionally hot weather period in 2007, the highest cooling effect of 2.2°C was found to be reached in a street with high tree shaded area and minimal traffic load (Tsiros 2010). These results imply the passive cooling potential of shade trees. Akbari et al. (2001) estimated that 20% of the cooling demand of the USA can be avoided through the implementation of heat island mitigation measures for instance by planting trees. In general, frequentation and use of green spaces could generate benefits and well being on people, especially during heat waves periods, and this could be explained by the capacity of green spaces to provide better thermal comfort (Lafortezza et al. 2009).

Air quality regulation

Air quality regulation refers to the role ecosystems play in regulating the gaseous portion of nutrient cycles that affect atmospheric composition. Air quality plays an important role during heat waves and can be a source of human illnesses during these extreme events. During a heat wave in urban areas, hot days are often followed by hot nights because of the heat island effect. These conditions can produce a high degree of heat and air pollution stress, especially for people with cardiovascular and respiratory disorders (Piver et al. 1999). For instance, in The Netherlands, 1,000–1,400 deaths were estimated because of the hot temperatures that occurred during the 2003 summer period, and of these, the number of deaths attributable to the ozone (O_3) and particular matter (PM_{10}) concentrations in the period June–August were estimated at around 400–600 deaths (Fischer et al. 2004). In France, the relative contribution of O_3 and temperature in the high mortality during the 2003 heat wave was heterogeneous among cities (Filleul et al. 2006). For the nine cities considered in their study, the excess risk of death for an increase of 10 $\mu g/m^3$ in O_3 level is significant (Filleul et al. 2006). In particular, between 3 and 17 August 2003, the excess risk of deaths linked to O_3 and temperatures together ranged from 10.6% in Le Havre to 174.7% in Paris, while the contribution of O_3 alone varied, ranging from 2.5% in Bordeaux to 85.3% in Toulouse (Filleul et al. 2006). In Croatia, a significant part of excess mortality, during the same period, was attributed to PM_{10} and O_3 in the air (Alebić-Juretić et al. 2007).

Due to their large leaf areas and their physical properties trees can act as biological filters. These can remove large numbers of airborne particles and hence improve the quality of air in polluted environments (Beckett et al. 1998; Nowak et al. 2000; Brack 2002; Jim and Chen 2008; Escobedo and Nowak 2009). In particular, trees can be effective in reducing the impacts of damaging forms of particulate pollution such as PM_{10} or gasses such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO) and CO_2, and are effective in reducing O_3 concentrations in cities (Nowak et al. 2000). The effectiveness of this ecosystem service varies according to plant species, canopy area, type and characteristics of air pollutants, and local meteorological environment. Larger trees extract and store more CO_2 from the atmosphere and their greater leaf area traps air pollutants, casts shade and intercepts rainfall run-off (Brack 2002). Uptake happens mainly through dry deposition, a mechanism by which gaseous and particulate pollutants are transported to and absorbed into plants mainly through their surfaces. In urban areas, districts with more extensive urban trees capture more pollutants from the air, and this capacity is increased as trees gradually reach final dimensions (Jim and Chen 2008). In general, the effectiveness of uptake by trees of particles >5 μm is increased if their leaf and bark surfaces are rough or sticky (Beckett et al. 1998). For smaller particles the most effective uptake happens in the needles of conifers. Due to the larger total surface area of needles, coniferous trees have a larger filtering capacity than trees with deciduous leaves, with pines (*Pinus* spp.) capturing significantly more material than cypresses (*Cupresses* spp.) (Beckett et al. 2000). In addition, this capacity is also greater because the needles are not shed during the winter, when the air quality is usually worst (Bolund and Hunhammar 1999). According to Jim and Chen (2008), most removal occurs in the winter months mainly due to the higher pollutants concentrations. However, coniferous trees are also more sensitive to air pollution and deciduous trees are better at absorbing gasses (Bolund and Hunhammar 1999). Veteran trees (i.e. trees that have lived a long time and are significant elements of the landscape) often contribute substantially more benefits to society relative to other (smaller) trees in the landscape (Nowak 2004). For instance, veteran trees will store, due to their increased size, larger amounts of carbon in their tissues. Interception of particles by vegetation seems also to be much greater for street trees, due to their location in proximity to high road traffic (Beckett et al. 1998). Trees situated close to a busy road capture significantly more material, especially larger particles, than those situated in a rural area (Beckett et al. 1998). In Chile, it has been demonstrated that Santiago's urban forests are effective at removing PM_{10} (Escobedo and Nowak 2009). In 1991, trees in the city of Chicago (11 percent tree cover) removed an estimated 15 metric tons of CO, 93 tons of SO_2, 98 tons of NO_2, 210 tons of 0_3 and 234 tons of PM_{10} (McPherson et al. 1994). Similarly, the peri-urban vegetation of the Madrid region constitutes a sink of O_3, with evergreen broadleaf and deciduous tree species removing more atmospheric O_3 than conifer forests. Nowak et al. (2000) modelled the effects of increased urban tree cover on O_3 concentrations (13–15 July 1995) from Washington, DC (USA), revealing that urban trees generally reduce O_3 concentrations in cities.

Jim and Chen (2008) assessed the capability and monetary value of the removal by urban trees of air pollution in Guangzhou city in South China. The researcher found that an annual removal of SO_2, NO_2 and total suspended particulates of about 312.03 mg, and the benefits were valued at RMB 90.19 thousand. Overall, there are few known studies that analyse differences in urban forest structure and air pollution removal in sub-regions of a city, and there are even fewer studies that link a city's urban forest structure and socioeconomic activity with site-specific pollution dynamics through time (Escobedo and Nowak 2009).

Impacts of heat waves on ecosystems in and around urban areas

As showed in Fig. 1, hydro-meteorological hazards can also affect ecosystems, such as forests and water systems, and their services in urban and peri-urban areas. In the summer 2003, the drought experienced by the vegetation was worsened by the length of the period with scarce precipitations and humidity, by the heat during the summer and the longer duration of the sunshine period (Rebetez et al. 2006). In the course of a drought, the gradually decreasing rate of passage of either water vapour or CO_2 through the stomata, or small pores of the plant, assimilation and growth are observed (Leuzinger et al. 2005). Fires can also affect vegetation during heat waves or periods of drought. During the 2003 heat waves, small-scale forest fires were observed all over central Europe and the western Mediterranean (Fink et al. 2004).

Trees can be directly affected by air pollutants depending on the types and concentrations. The most common effects of plant exposure to O_3 are modifications of stomata behaviour, which leads to a reduced photosynthesis and an increased respiration. As gas, NO_x and SO_2 damage cuticles and stomata and, most importantly, they penetrate through stomata and alter tissues. SO_2 can cause both acute (e.g. cell plasmolysis) and chronic injury (e.g. reduced gas exchange, chlorophyll degradation, chloroplast swelling, and alteration of cellular permeability). As mentioned above, after a certain threshold is reached trees can be affected by nutrient stress, reduced photosynthetic or reproductive rate, predisposed to entomological or microbial stress, or direct disease induction (Smith 1974).

In the urban context, water bodies and wetlands are often beneficial for transportation, recreation, dilution and purification. On the other hand, urbanisation is thought to cause: "reduced baseflows, increased frequency and magnitude of peak discharges, increased sediment loads, impaired water quality, reduction in channel and floodplain complexity" (LeBlanc et al. 1997). Water quality may further deteriorate to critical values during periods of prolonged low-flow conditions in combination with high water temperatures. In the Meuse river basin, which flows through the cities of Namur and Liège in Belgium, during the 1976 and 2003 heat waves, deterioration of water quality by high water temperatures, eutrophication, increased concentrations of major elements and some metals or metalloids (selenium, nickel and barium) were measured (van-Vliet and Zwolsman 2008). However, concentrations of nitrate and some heavy metals with high affinity for adsorption onto suspended solids (i.e. lead, chrome, mercury and cadmium) decreased, which also positively affected chemical water quality during drought (van-Vliet and Zwolsman 2008). Overall eutrophication, following hot spells, causes major impacts on the water system.

During a heat wave event, temperature of lakes can rise until reaching record temperatures (increase varies between 1 and 3°C on average) (Jankowski et al. 2006). Jankowski et al. (2006) investigated the consequences of the 2003 European heat wave for lake temperature profiles, thermal stability (i.e. suppressing downward turbulent mixing) and hypolimnetic oxygen depletion. Warming of water bodies can restrict lake overturning and lead to anaerobic conditions, thus potentially seriously impacting aquatic ecosystems, leading, in the summer, to the development of harmful cyanobacterial blooms. Oxygen depletion may lead to negative ecological consequences such as phosphorous dissolution from the sediments leading to internal loading and algal blooms (Jankowski et al. 2006). Surface blooms of toxic cyanobacteria in eutrophic lakes may lead to mass mortalities of fish and birds, and affects cattle, pets, and humans (Jöhnk et al. 2008). This may have impacts on recreational activities, fishing and surface water sports. In sport fisheries, increased water temperature has been associated with decreased activity and movement to deeper cooler waters, which reduces fish catches.

Concerning water quantity, most of the studies agree that wetlands reduce the flow of water in downstream rivers during dry periods. In fact evapotranspiration from wetlands is shown to be higher than from other portions of the catchment during these periods (Bullock and Acreman 2003). For groundwater resources, prolonged heat stress may lead to lowered water table levels. In urban areas, the impairment of soils aggravates the magnitude of this impact because the reduced infiltration reduces the water table. Lower water table levels were measured in urban areas (Scalenghe and Marsan 2009).

Floods

Floods as a hazard

The European Union Floods Directive defines a flood as a temporary covering by water of land not normally covered by water. According to Few et al. (2004), flood disasters and their mortality impacts are heavily concentrated in Asia, where there are high population concentrations in floodplains, such as the Ganges, Brahmaputra, Mekong and Yangtze basins, and in cyclone-prone coastal regions such as around the Bay of Bengal and the South China Sea. Floods affecting urban areas can be either generated locally or in other locations in the watershed and basin. Urban areas often generate impacts on watershed-wide ecosystems such as through land use changes and infrastructure development, which affects watercourses. When dealing with floods, it is therefore important to consider the role of ecosystems not only within the urban areas themselves, but also in the entire landscape of the watershed and the influences urban areas have on them (PEDRR 2011). These two scales of analyses are considered in this section with a focus on urban areas.

Floods are the result of meteorological and hydrological factors, but anthropogenic modifications can also play a role in defining the magnitude of the event. Therefore, floods in urban areas are the result of natural and man-made factors. Although these influences are very diverse, they generally tend to aggravate flood hazards by accentuating flood peaks. As a result of different combinations of factors, urban floods can basically be divided into four categories: local floods, riverine floods, coastal floods and flash floods. Floods in urban areas can be attributed to one or a combination of the above types. The main cause of urban flooding is a severe thunderstorm, which is generally preceded by a long but moderate rainfall that saturates the soil. Therefore floods in urban areas are, in general, flash floods that expand both on impaired surfaces and in surrounding parks and streets (Andjelkovic 2001). Other causes of urban floods are: "inadequate land use and channelization of waterways; failure of the city protection dikes; inflow from the river during high stages into urban drainage systems; surcharge due to blockage of drains and street inlets; soil erosion generating material that clogs drainage system and inlets; inadequate street cleaning practice that clogs street inlets" (Andjelkovic 2001).

Major destructive flooding events occurred in Europe in the last few years: floods in the Elbe basin in 2001 that produced losses of over 20 billion Euros; floods in Italy, France and the Swiss Alps in 2000 costing around 12 billion Euros and a series of floods in the UK during summer 2007 accumulating losses of more than 4 billion Euros (EEA 2010a). Losses as a consequence of floods have increased in the past decades in Europe. While there is no evident trend over time in respect to the number of fatalities and observations do not show a clear increase in flood frequency (Mudelsee et al. 2003), increases in population and wealth in the affected areas are the main factors contributing to the increase in losses (EEA 2010a).

Impacts of urbanisation on ecosystems

When degraded by a variety of human activities and changing climatic conditions, hydrologic regimes typically have increased frequency and severity of flooding, lowered water tables and reduced groundwater recharge compared to previous, more "natural" conditions (Cai et al. 2011).

At the river basin level, urbanisation directly affects catchments hydrology by changes in surface runoff, groundwater runoff, groundwater levels and water quality. The introduction of impervious surfaces inhibits infiltration and reduces surface retention (Packman 1980). Thus the proportion of storm rainfall that goes to surface runoff is increased, and the proportion that goes to evapotranspiration, groundwater recharge and base flow is reduced. This increased surface runoff is combined with an increase in the speed of response and increased peak discharge, which can lead to floods (Packman 1980; Nirupama and Simonovic 2006). For instance, in the Upper Thames River watershed in Canada, urban areas have increased to 22% of the total watershed area in the year 2000 compared to only 10% in 1974, enhancing the risk from river flooding (Nirupama and Simonovic 2006). On the other hand, in the Dead Run watershed (14.3 km^2) in the Baltimore, MD, region, the current tree cover is 13.2% with an impervious cover of 29%. Increasing tree cover in the watershed to 71% is estimated to reduce total runoff in the watershed by about 5% for the simulation period of the year 2000 (Nowak 2006). Li and Wang (2009) analysed the urban expansion of St. Charles County, a suburb of St. Louis, MO, located in the Dardenne Creek watershed. A rapid increase of urban areas in the watershed took place from 3.4% in 1982 to 27.3% in 2003, and model simulations suggested an increase in more that 70% in average direct runoff in the watershed from 1982 to 2003, correlated with urban expansion.

At the urban scale, more radical changes in surface characteristics and soil sealing (i.e. the covering of soil for housing, roads and parking lots, etc.) increase the impermeability of soils, drainage and water run-off and lead to rapid precipitation run-off, flooding, erosion and impervious surfaces cause: "local decreases in infiltration, percolation and soil moisture storage, reductions in natural interception and depression storage and increases in runoff" (Brun and Band 2000). Severe storms may also yield discharges exceeding the capacity of the sewer system, causing choking of the flow and increased attenuation in localised ponding. The soft ground of vegetated areas allows water to seep through, and the vegetation takes up water and releases it into the air through evapo-transpiration (Bolund and Hunhammar 1999). Urban sprawl with moderate to high soil sealing over a large area reduces the infiltration potential of the soil and increases the flood risk of urban areas (EEA 2010a). Soil sealing also impacts the porosity of soils by reducing it or by modifying its pattern, which reduces water infiltration (Scalenghe and Marsan 2009). In the surroundings of urban areas the amount and the speed of flooding water that arrives on unsealed surfaces are increased and increase the risk of ponding and erosion (Scalenghe and Marsan 2009). In these areas, when human population increases with urban sprawl, wetland's functions can easily be affected with pollution or recreational activities (Mitsch and Gosselink 2000). In these conditions, wetlands can no longer effectively reduce floods, sequester pollutants or host different biota (Mitsch and Gosselink 2000). Thus wetland value appears to be maximum when close to the river system and distributed spatially across an environment that is not dominated either by cities or agriculture, but one that balances nature and human aspects (Mitsch and Gosselink 2000).

Water regulation

The role of forests and soils

On the local scale, forests and forest soils are capable of reducing runoff generally as the result of enhanced infiltration and storage capacities. At the river basin scale, this holds true for small-scale rainfall events in small catchments, which are not directly responsible for severe flooding in downstream areas (FAO and CIFOR 2005). The geomorphology of the area and the preceding rainfall seem to be the two most important factors in determining the magnitude of the flooding event: the amount of storm flow is most directly linked to the area in the watershed and volume of precipitation or snowmelt deposited on the site, stored or transported to the stream (Eisenbies et al. 2007). Overall, forests seem not to be able to stop large-scale floods, which are caused by severe meteorological events (Eisenbies et al. 2007).

According to the physical properties of soils, some, not heavily affected by human activities, have a large capacity to store water, facilitate transfer to groundwater, and prevent and reduce flooding (MA 2005). The initial conditions of soil saturation in a basin determine the manifestation and the intensity of a flood event. In conditions of low soil saturation, water percolates in the soil and flood risk is diminished (Lahmer et al. 2000). While in conditions of high soil saturation, additional precipitation is rapidly transferred to the river through surface runoff or by interflow (Lahmer et al. 2000). When the soil becomes saturated and loses its ability to store further water, there does not seem to be any evidence that forests and their soil have a noticeable effect in regulating floods for the extreme rainfall conditions that lead to major flooding events (Balmford et al. 2008). However, evidence indicates that the key factor linking land use and flood regulation is soil condition rather than the trees, and that much of the soil degradation associated with deforestation results from poor land use practices (e.g. soil compaction during road building, overgrazing, litter removal, destruction of organic matter, clean weeding) (Balmford et al. 2008).

The role of wetlands

Wetland, floodplain, lake and reservoir ecosystems play an important role in the regulation of floods in inland systems and provide protection from the adverse consequences of natural hazards to humans, even for urban areas. In particular, wetlands are significant in altering water cycle and perform hydrological functions (Bullock and Acreman 2003). Floodplain wetlands reduce or delay floods; on the other hand most of the studies show that wetlands located upstream in a watershed tend to be quickly saturated and increase the risk of flash floods (Bullock and Acreman 2003). If wetlands are too small, functions, such as storage of floodwater (for mitigation of floods), no longer exist: it has been assessed that 3–7% of the area of a watershed in temperate zones should be maintained as wetlands to provide both adequate flood control and water quality improvement functions (Mitsch and Gosselink 2000). Effective control is more often the result of the combined effect of a series of wetlands within a catchment area instead of single units. Some authors argue that, to maintain the pulse control function of wetlands, a greater number of wetlands in the upper reaches of a watershed is preferable to fewer larger wetlands in the lower reaches [Loucks (1989) cited in Mitsch and Gosselink (2000)]. A modelling effort on flood control suggested the opposite: the usefulness of wetlands in decreasing flooding increases with the distance of the wetland downstream [Ogawa and Male (1986) cited in Mitsch and Gosselink (2000)]. Further research is therefore needed in order to determine the real effects of wetlands and their position in the landscape in terms of buffering urban areas from floods.

Impacts of floods on ecosystem services

While floods provide a series of benefits (e.g. nutrients deposition), these hazards can also affect ecosystems especially when the environment has been degraded. For instance, flooding and submergence are responsible for major abiotic stresses and, together with water shortage, salinity and extreme temperatures are the major factors that determine species distribution (Visser et al. 2003). Overall, only pioneering species are able to locate in zones close to the river (Blom and Voesenek 1996), and floods have a greater impact on plant species during the growing season (Kozlowski 1997). Plant responses to flooding during the growing season include: “injury, inhibition of seed germination, vegetative growth, and reproductive growth, changes in plant anatomy, and promotion of early senescence and mortality” (Kozlowski 1997). Adaptive strategies and flood tolerance of plants depend on plant species and genotype, age of plants, frequency, duration, timing and conditions of flooding (i.e. soil flooding, water logging, total submergence of vegetation) (Kozlowski 1997; Vervuren et al. 2003). Underwater light intensity and depth of the water column may also affect survival during periods of submergence (Vervuren et al. 2003).

Flooding also changes the physical status of soils, which may severely affect peri-urban agricultural practices. For instance, water logging causes the breakdown of large aggregates into smaller particles, deflocculation of clay and destruction of cementing agents. As the water level declines, these small parts of soil are redistributed in a new, more dense structure, creating: “smaller soil pore diameters, higher mechanical resistance to root penetration, low O_2 concentrations and the inhibition of resource use” (Blom and Voesenek 1996) and the accumulation of CO_2 in soils (Kozlowski 1997). Gas diffusion is severely inhibited during flooding (Blom and Voesenek 1996): oxygen remains in the soils and is consumed by aerobic processes (roots and soil organisms), nutrient availability for plants strongly decreases and anaerobic processes take place producing toxic substances for plants [lowering of soil redox potential (Eh)]. Chemical changes also include the increased solubility of mineral substances, reduction of Fe, Mn and S, and anaerobic decomposition of organic matter. The reduction condition (i.e. low soil Eh) is also a major factor in wetland ecosystems that influences plant survival, growth and productivity (Pezeshki 2001). Floods can also cause secondary impacts, for instance affecting industries and in particular petrochemical ones, causing the release of toxic chemicals, which further impact the environment.

Policy initiatives for the protection of urban ecosystem services for disaster risk reduction

At the international level, policy initiatives that target any of the three points of policy leverage identified in Fig. 1, are rare. The United Nations International Strategy for Disaster Reduction's (UNISDR) Hyogo Framework for Action 2005–2015 lists "sustainable ecosystems and environmental management" as one of the main pillars for reducing underlying risk factors (UNISDR 2005). Calling for an improved management of ecosystems and their services for disaster risk reduction, this initiative directly targets arrow 2 of the framework in Fig. 1. Paragraph 19 of the Hyogo Framework can be situated in correspondence to arrow 3 of the framework as it establishes the Priority for Action 4: "Reduce the underlying risk factors", which include: "Incorporate disaster risk assessments into urban development planning and management of disaster-prone human settlements" … "rural development" … "major infrastructure" … "including considerations based on social, economic and environmental impact assessments". In addition the UNISDR campaign on Making Cities Resilient proposes a 10-point checklist to serve as a guide for commitment by Mayors (UNISDR 2010). Point 8 makes explicit the need to consider the environmental dimension: "Protect ecosystems and natural buffers to mitigate floods, storm surges and other hazards to which your city may be vulnerable. Adapt to climate change by building on good risk reduction practices" (UNISDR 2010, p. 9).

At the local and regional levels, policy initiatives are very few for the incorporation of ecosystem preservation for disaster risk reduction in urban areas. At the European level, the Communication from the Commission to the European Parliament "Options for an EU vision and target for biodiversity beyond 2010" identifies four policy options to halt the loss of biodiversity and ecosystem services by 2020 but with no reference to disaster risk reduction (EC 2010). For European countries, notably the UK, The Netherlands and Germany, affected by severe flooding in recent years, have made policy shifts to "making space for water", represented by arrow 2 of the framework (Fig. 1). New risk management policies and practices favour a more holistic approach to flood risk management based on River Basin Management Plans, Integrated Coastal Zone Management to enhance natural processes.

Regarding heat waves, the London local government authorities have developed the "Right Trees for a Changing Climate" database and website to provide advice on planting the right trees in the right place, based on the fact that planting more trees, alongside increasing other green cover, is one of the ways in which London can adapt to climate change (http://www.right-trees.org.uk/default.aspx), using vegetation to keep the city cool. The city has set ambitious targets to: increase tree cover by 5% by 2025; increase greenery in the centre of London by 5% by 2030 and a further 5% by 2050; create 100,000 m^2 of new green roofs by 2012; and enhance 280 hectares of green space by 2012. Stuttgart has planned to exploit the role of natural wind patterns and dense vegetation in reducing problems of overheating and air pollution. A Climate Atlas was developed for the Stuttgart region, presenting the distribution of temperature and cold air flows according to the city's topography and land use. Based on this information, a number of planning and zoning regulations are recommended that aim to preserve open space and increase the presence of vegetation in densely built-up areas (Kazmierczak and Carter 2010). In Stuttgart the preservation of the natural environment in urban areas is principally guided by the Federal Nature Conservation Act (BNatSchG), which prohibits the modification or impairment of protected green spaces, or changing land use in these protected areas (i.e. "zones in settlement areas, parks, cemeteries, significant gardens, single trees, lines of trees, avenues or groves in settled or unbuilt areas; and some plantings and protective wood outside forests") (Kazmierczak and Carter 2010). London and Stuttgart have thus put in place policies that focus on arrow 2 and 3 of the framework presented in Fig. 1, meaning that they call for ecosystem conservation and an improvement of urban planning.

Other examples of the implementation of projects and policies to protect cities from hydro-meteorological hazards through the restoration and management of ecosystem services come from the US and Lao PDR. The "Grow Boston Greener (GBG)" is a collaborative effort of the city of Boston (USA) and its partners to increase the urban tree canopy cover in the city by planting 100,000 trees by 2020. The planting of these trees will increase Boston's tree canopy cover from 29 to 35% by 2030 as the planted trees mature. The goals are to: "increase the tree canopy cover in low canopy areas; mitigate the urban heat island effect and reduce energy consumption through the appropriate placement of trees on residential and commercial properties; improve air quality; and improve storm water management through strategic neighbourhood plantings" (http://people.tribe.net/phoenix_fire_nectar/blog/bfacb2b9-300a-4a28-9ac9-48681de04b07). This case is interesting as it considers the multiple benefits and services that can be derived by the same ecosystem, in this case the urban forest.

"Integrating Wetland Ecosystem Values into Urban Planning: The Case of That Luang Marsh" is an economic assessment of the goods and services provided by the marshes in an attempt to examine the economic value of urban wetland biodiversity and its importance to people living around the wetland as well as the larger urban area of Vientiane (Gerrard 2004). Wetlands and marsh areas in and around the city are important physical features and provide hydrological functions such as flood control. There are currently 175 flood-prone areas within the city limits, 70 of which are located in the city's core area. Flooding occurs at least six times a year but in many cases flood-prone areas will flood every time it rains. In the urban area of Vientiane flooding is not deep, but frequent flooding causes damage to buildings and roads, and interrupts transportation. The value of the regulating ecosystem service has been measured as the annual value of flood damages avoided in these areas and it will amount at close to US$ 3 million by the year 2020 (Gerrard 2004).

Conclusions

Basing our analysis on the conceptual framework of Fig. 1, we reviewed how locally and regionally generated and well-managed ecosystem services can contribute to lower the vulnerability of urban communities to hydro-meteorological hazards such as heat waves and floods. We also reviewed studies that quantify, when possible, the role of these ecosystem services.

Urban areas will continue to attract people who want to settle in them because of the many economic advantages they provide. It is therefore critical for urban areas to provide safe livelihoods to their populations, and although urbanisation will always imply a change in ecosystems and the services they provide, urban planning should systematically consider the role of ecosystems in buffering and mitigating the effects of environmental hazards such as heat waves and floods. In this respect, urban areas would benefit from the restoration and adequate management of ecosystems. Urban planners and managers should take into consideration the role of ecosystems in reducing risks and vulnerabilities (arrow 2 of Fig. 1). When establishing urban development plans the presentation of landscape plans and green open space structure plans should be taken into account (arrow 2 and 3 of Fig. 1). Although urban areas will generally create similar types of effects when it comes to heat waves and flooding, the specific local climatic conditions (e.g. urban heat island effect) will dictate the magnitude and frequency of the hazards and the urban ecosystems the potential to buffer these. There are therefore no generic sets of solutions to address the problems globally, but adapted solutions need to be sought regionally or locally. On the other hand, while designing strategies that make use of ecosystem services to buffer cities, it is important to take into consideration the effects of hazards on the ecosystem itself (arrow 1 of Fig. 1). For instance, the right type of trees (i.e. in general native species) or the right succession that is more resistant to the impacts of hydro-meteorological hazards should be identified to be planted. Overall we have sufficient ecological knowledge on how cities can be buffered by ecosystem services with respect to the reviewed hydro-meteorological hazards. But we know little on how to measure ecosystem services for hazard regulation, which is an obstacle towards the design and implementation of appropriate policies and plans. We propose here a series of general recommendations to fill this gap:

- ecosystem conservation and restoration play an important role in lowering the vulnerability of urban areas to hydro-meteorological hazards. A meta-analysis of 89 restoration assessments in a wide range of ecosystem types across the globe indicates that ecological restoration increased provision of biodiversity and ecosystem services by 44 and 25%, respectively (Benayas et al. 2009);
- the vulnerability of urban communities and ecosystems to hydro-meteorological hazards is influenced and aggravated by the impacts of these hazards on ecosystems and urbanisation. It is therefore necessary to integrate disaster risk reduction, appropriate urban planning and ecological restoration. For instance, in areas where land-use pressure is considerable, ecosystem services can be secured by leaving green and blue areas in close proximity to one another, so that these areas form larger nature and landscape entities (Niemelä et al. 2010);
- one ecosystem my provide services for the regulation of more than one type of hydro-meteorological hazard, as is the case for green areas in cities. It is therefore recommended to adopt a multiple-hazard approach;
- generally cities are located in a watershed. The management of ecosystems for the protection of cities from hydro-meteorological hazards at this scale, which transcends administrative boundaries, can provide important elements of comparison of the vulnerability of different cities.

Urban ecosystems provide essential services to cities and city dwellers that are exposed to heat waves and floods.

Given the rapid urbanisation throughout the world and the likely impacts of climate change in terms of these two hazards, it is urgent to manage these ecosystems in a better way than has been done in the past through integration of ecosystem management in urban planning and disaster risk reduction.

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