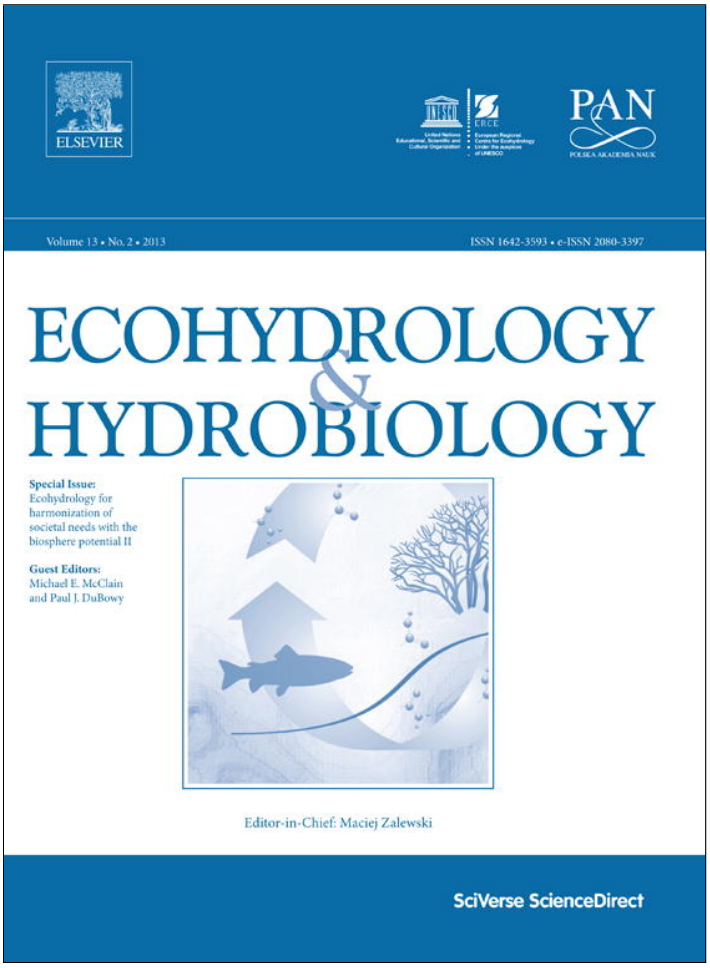
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Original research article

The role of ecohydrology in creating more resilient cities

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ABSTRACT

The increasing global rate of urbanisation and concurrent global climate changes create new challenges and new opportunities for managing cities, water resources and related quality of life. In most strategies, however, water ecosystems, which are the fundamental component of the integrated urban water resources management (IUWRM), are regarded as objects of protection or rehabilitation; not, as postulated by ecohydrology, as management tools. This paper addresses the possibilities of: (i) the functional incorporation of aquatic ecosystems into the IUWRM; (ii) optimising their functioning by local ecohydrological approach; and (iii) integration of ecosystem functions on a city scale to build system solutions for more resilient cities. Two case studies of the UNESCO MAB/IHP demonstration network representing different urban development patterns are given. The City of Łódź (Poland) uses water-resource based urban retrofitting for improving the quality of life and attracting inhabitants, departing from the analysis of longitudinal dynamics of nutrient transition in the river–reservoirs system, towards proposing an alternative concept of spatial city development. The city of Lyon (France), with intensive periurban development and population growth, provides a hierarchy of stream reaches to cope with combined sewer overflows to help municipalities to better position future urban runoff outlets. This article envisions also the future management of urban waste and storm waters using urban rivers, assuming resilient cities will depend on the integrity of environmental, technical and spatial planning decisions. The virtues of ecohydrology are discussed in this respect.

1. Introduction

1.1. Challenges for the cities of the future

It took about 12,000 years, from the beginning of contemporary human civilisation (10,000 BC), until the time of the industrial era (c.a. 1800), for the human population to reach its first billion. The next six billions were reached only in 200 years (in 2011), and the next two will come in the next 30 years (in 2050; UNFPA, 2007). Most of this rapid increase has taken place in cities. Despite occupying only 2% of the continental surface, they are home to more than half of the human population, approaching 70% in 2050. They contribute to 55% of the Gross National Product in less developed countries and 85% in more developed ones. They also use up ¾ of the natural fossil and renewable resources and energy production, and contribute to ¾ of greenhouse gas emission (UNEP, 2009). In the future, cities will continue to play a major economic role, as well as contribute to further environmental degradation through resource consumption, waste generation and pollution.

The degree, pace and nature of urbanisation significantly differ between regions, individual countries and cities (UN-HABITAT, 2008) and depend on demographic

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change, migration and reclassification of administrative borders. The urban population growth is usually connected with spatial expansion of cities, however, it is increasingly the case that spatial expansion takes place together with a decrease in population size. In the latter case, cities grow like a donut: empty in the middle and expanding outwards. A number of social and economical challenges generated by such a model include abandoned or inefficiently used infrastructure, decreasing tax revenue, weakening social connections, lowering security and increasing city management costs, to mention just a few. Both trends, contribute to urban sprawl (Arribas-Bel et al., 2011; Galster et al., 2001; Habibi and Asadi, 2011), and create number of ecological, social and economic challenges (UNFPA, 2007), including considerable direct and indirect impacts on water resources (Haase and Nuissl, 2007). Increased consumption of the area outside cities and consequent landscape degradation leads to a loss of biodiversity and disconnection of ecosystems, resulting in decreased ability of ecosystems to provide services, such as water and nutrient retention, regeneration of water and air quality, assuring space for recreation. Increased impact of growing population and urbanisation on water resources (i.e., water consumption, limited aquifer augmentation, pollution, physical degradation of water ecosystems and their connectivity with water-dependent ecosystems and groundwater).

Global climate change, and the resulting destabilisation of the water cycle is expected to further add to these challenges. Predicted prolonged droughts and more frequent intensive precipitation will directly impact the cities with increased frequency and intensity of floods and droughts (Radojevic et al., 2010; Vrochidou et al., 2013). Higher temperatures will increase length, frequency and intensity of the urban heat island (UHI). The resultant microclimate change and poor air quality will further compromise the environmental security, health and quality of life of cities' inhabitants. Over the last decades, heat waves have already caused tens of thousands of premature deaths in Europe (EEA, 2012), and outdoor air quality has been recognised as a top level risk for public health (GBD, 2012).

1.2. Resilient cities

How can a safe life be assured for a burgeoning urban population, within cities suffering increasing vulnerability and a weakening global economy?

Boosting (bio-) technological innovations is one of the answers to the escalating tensions (Novotny, 2010), while developing of innovative concepts and approaches is just as important. In this perspective, urban dynamic creates evident threats, but it also brings about new opportunities by challenging management frameworks, creating a demand for new ideas and best practices, towards a more resilient solutions.

Novotny (2010) developed the idea that "cities are both the problems and solutions to sustainability challenges of an increasingly urbanised world". The way to ensure the resilience of a city would rely on the management of its ecological footprint (Rees and Wackernagel, 1996), in the sense of using geographically connected lands (Luck et al., 2001) to reduce long distance hazard connexions and greenhouse gas emissions, and by developing the internal recycling of its waste, including water (Grimm et al., 2008a,b; Novotny, 2010).

The concept of resilience applies to many domains, from mechanics and industrial production to living systems. For complex systems, a measure of resilience is the time required to return to a previous stable functioning state after a disturbance. The concept was theorised and demonstrated from the field observations in ecology (Holling, 1996). Following this inspiration, resilient cities are also assumed to be flexible enough to cope with near-future impacts: global climate change and urban population increase. The leading ideas in the design of sustainable urban systems were proposed during recent decades. An early vision was the "ecocity concept" (Register, 1987) based on the balancing of social, economic and environmental factors, which are interdependent by nature, and constitute a triple bottom line which defines the city of the future. As water is both a vital resource and a main carrier for other city fluxes i.e., nutrients and energy, future cities should be energy- and water-frugal, based on a hydrologically functioning landscape, and maintaining the interconnexions between water bodies and natural adjacent landscapes.

A more comprehensive definition of a resilient city emphasises the general capacity and ability of a community to withstand stress, survive, adapt and bounce back from a crisis or disaster and rapidly move on. It refers to the societal benefit of collective efforts to build collective capacity and the ability to withstand stress (ICLEI, 2012). Such an approach includes such diverse aspects as community-based risk assessments, disaster and risk reduction; integrated urban planning, development and logistics; integrating solutions into all aspects of city management (system solutions); addressing most vulnerable groups; financing, including the private sector; cooperation and implementing process on the ground; decision supporting tools, legislation and flexible implementation networks; political will; integration of environmental aspects: green urban economy, urban agriculture, green infrastructure, renewable energy (ICLEI, 2012).

All the above components create the potential to manage urban water ecosystems in a more efficient way, and to incorporate them as important components of system solutions. However, this opportunity is not always sufficiently recognised and used. Therefore, the aim of this paper is to present some aspects of water ecosystem resilience which may contribute to the overall concept of a resilient city.

1.3. The urban water cycle: coupling environment and technology to better address future issues

There are three global problems with water: too much, too little, too dirty (Kundzewicz and Kowalczak, 2009), and three reasons why they strongly apply in urban areas.

Firstly, landscape change due to high density of development has profound effect of the water and heat balance. High percentage of impermeable surface in the urban area reduces evapotranspiration, infiltration and groundwater recharge and increases surface runoff, comparing to the reference conditions. This effect, first described by Leopold (1968), is now escalating further as a result of urbanisation and global change (Stone et al., 2010; Willems et al., 2012).

Secondly, in urban areas, environmental elements of the water cycle are tied to ageing technical (grey) infrastructure intended for the provision of water, collection and treatment of sewage and drainage of storm water. This infrastructure is fundamentally highly inflexible because of its definite parameters, which are not able to adapt to changing conditions and emerging threats. In case of stormwater management, for instance, both combined sewer systems, which are common in most European cities, and separated stormwater drainage (''end-of-pipe'' approach) are not able to absorb increasing, occasional fluxes due to fixed inlets and pipes diameters, which often drain bigger catchments with higher percentage of impermeable areas, than it was originally designed. Its operation is also governed by the requisites of urban organisation and structure, such as available space for new housing, connections and treatment facilities, rather than the capacity of the receiving rivers.

Finally, the negative consequences of the above changes impact the ecological security and the quality of life of a large number of people per unit area.

The combination of the above factors results in several risks to urban water management, such as increased pluvial flooding, enhanced hydraulic and pollutant loading to already capacity-constrained drainage systems and higher frequency of untreated overflows from combined sewer overflows (CSOs), directly degrading receiving aquatic ecosystems. Fluxes of water, pollutants and matter are several orders of magnitude larger, and much more violent at point (CSO) location than would be the case under natural or even agricultural conditions, resulting in well-known impacts that are now addressed by national laws (e.g., EPA, 2007). On the other hand, evacuating large amounts of stormwater as fast as possible from the city, dries the urban environment, depriving it of a valuable source of water, which would normally support environmental processes.

It is well known that problems cannot be solved by using the same thinking that was used when they were created. Thus, further investment in hard infrastructure undoubtedly increases the costs of urban water management (e.g. O'Connor and Field, 2005), but does not contribute to a resilient solution. There is a need to seek sustainable approaches supporting specific components of the urban water cycle and related infrastructure (Marsalek et al., 2008). Therefore, recent years have brought several innovations to address the limitations of the conventional approach in the urban water management. Its basic sectors (water provision and sewage treatment) are complemented with new areas (stormwater management and, recently, ecosystems), are subjects of innovation and better integration. (Fig. 1).

The water provision sector has moved towards water provision and reuse measures (Gijzen, 2006; UNEP, 2005). In the sewage treatment sector, there is a tendency towards including more decentralised elements based on local treatment technologies instead of centralised treatment plants, and grey and black water treatment (Novotny, 2010). Great change has been made in the stormwater management and ecosystems sectors, which are most relevant to this paper.

Stormwater management has greatly evolved from the ''end-of-pipe'' towards a holistic, integrated approach based on rainwater harvesting and ''source control'' approach (Marsalek and Chocat, 2002). Several existing source control approaches, differ in terms of their complexity and scope, but all aim at restoring local stormwater infiltration and retention, delaying formation of runoff and its controlled release and improving the water balance in the urban landscape. Best Management Practices (BMPs), as defined by the US Environmental Protection Agency, provide a number of structural and non-structural solutions for storm water retention and treatment. An equivalent of the structural solutions of BMPs is collectively known in the UK as Sustainable Urban Drainage Systems (SUDS; e.g., CIRIA, 2000), or Decentralised Rainwater/Stormwater Management in Germany (Hoyer et al., 2011).

Finally, the urban water cycle has been considerably expanded by the role of ecosystems, which in the conventional approach were limited to sewage receivers or eventually, in case of large rivers, aesthetic components contributing to the image of a city, such as The River Thames, Seine or Danube. Nowadays, ecosystems are becoming increasingly recognised as essential elements of the structure of cities, i.e., as blue and green infrastructure (EEA, 2012a; EPA, 2010; Kazmierczak and Carter, 2010) providing ecosystem services to the cities' inhabitants (Novotny, 2010).

Furthermore, integration among the above sectors is nowadays present to a greater extent than ever before in the context of Integrated Urban Resource Water Management (IURWM). Other examples of such a broader approach, which integrate onsite design and city planning techniques while also conserving natural systems, is proposed by the Low Impact Development (LID) approach developed in the US (EPA, 2000) and Water Sensitive Urban Design (WSUD) developed in Australia (SCWSC, 2009) which is becoming increasingly popular also in Europe (Hoyer et al., 2011).

1.4. *Perspectives for application of ecohydrology in urban areas*

Providing ecosystem goods and services by urban water ecosystems relies mostly on their functioning, which is limited by both urban development in a catchment (''external'' or ''upstream'' impact), and by the state of the ecosystem itself (''internal'' or ''instream'' conditions).

In this context, the stormwater source control and water sensitive urban planning practices are a milestone in reducing the ''external'' (or ''upstream'') impact of the urban catchment on water ecosystems. They improve chemical, physical and, to a certain extent, hydromorphological conditions for the functioning of water ecosystems, by reducing fluxes. Linked with on-site water saving

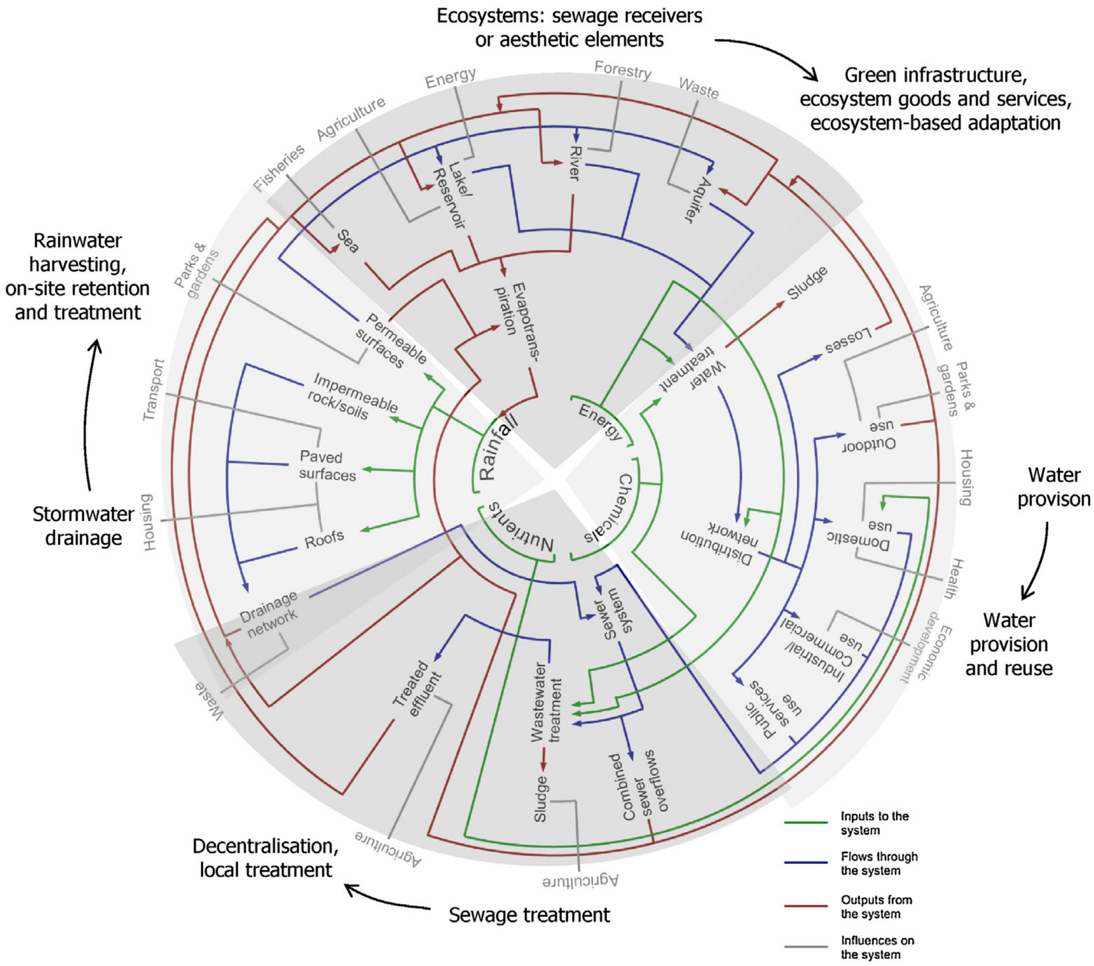


Fig. 1. The paradigm change in urban water cycle management towards innovation and integration of natural and technical elements. The arrows show changes in the approaches of the four key sectors of integrated urban water resources management (IUWRM): water provision, sewage treatment, stormwater control and ecosystem management.
The background urban water cycle graph by Philip and Salian (2011). Urban water cycle graph adapted from Philip and Salian (2011).

techniques assuring reduction in water consumption and disposal (Gijzen, 2006) they further stabilise the abiotic framework for ecological processes. The "internal" (or "instream") conditions, in case of rivers, can be usually improved by various measures of rehabilitation. They aim at improving both the ecological quality of the river and maintaining its anthropogenic use, which is still a new approach. In European urban rivers, the baseline for restoration include hydrology and hydrodynamics, morphology and connectivity, water quality, biodiversity and public health and safety and the ecological effects for restoration, and are, basically, measured by monitoring these parameters (Schanze et al., 2004).

The above approaches, especially when implemented jointly, substantially contribute to reducing stress and improving ecological status or the potential of urban rivers (Water Framework Directive, 2000/60/EC). However, the first approach perceives water ecosystems mostly from the perspective of being a "receiver" of the (reduced) impact, while the latter approach perceives them, mostly, as objects of structural rehabilitation. Ecosystems are not sufficiently recognised as active, functional, components of an IUWRM system, with the focus on their metabolism and its environmental drivers, such as hydro(geo)logy and geomorphic features which condition fluxes of energy provided to biota.

Strengthening the functional approach to water ecosystems is a proposal of the concept of ecohydrology (Zalewski et al., 1997; Zalewski, 2000, 2002). Ecohydrology is underpinned by an understanding of the interconnections between the catchment, providing a template for water and nutrient dynamics, on the one side, and biological processes from ecological succession, habitat modification, biological productivity down to nutrient circulation by the microbial loop on the other (Zalewski et al., 1997). This integration is used for "dual regulation", i.e. regulating biological processes by controlling the hydrological parameters of ecosystems and, vice versa, regulating hydrological processes by managing biota, with the goal of enhancing catchment/ecosystem resilience and its capacity against human impact, enhancing water and environmental sustainability and strengthening the provision of ecosystem services (Zalewski, 2006). The fundamentals of ecohydrological processes have been quantified and validated mainly in semi-natural systems both in terrestrial (e.g., Baird and Wilby, 1999; Eagelson, 1982; Kędziora and Olejnik, 2002; Rodriguez-Iturbe, 2000) and aquatic ecosystems (e.g., Agostinho et al., 2004; Mitsch et al., 2008; Zalewski, 2011; Zalewski et al., 2000, 2009; Wagner et al., 2009; Chicharo et al., 2001; Wolanski et al., 2004).

Translating experiences from natural systems into the urban ones in the face of dynamic urbanisation is a challenge. In particular, the potential enhancement of the absorbing capacity of ecosystems against human impact is an interesting possibility, considering high anthropogenic impact and limited urban space to implement measures (Wagner et al., 2008). In this frame the existence of biogeochemical hot spots and hot moments is of particular interest. They are defined as "areas (or patches) that show disproportionately high reaction rates relative to the surrounding area (or matrix)", at given time or location. Also "hot spots occur where hydrological flow paths converge with other flow paths or substances containing complementary reactants" (McClain et al., 2003). For point pollution, like with CSOs, hot spots would result from organic pollution creating specific local conditions.

The key questions are therefore: (i) how to incorporate the functionality of aquatic ecosystems into the IUWRM framework by the identification of natural metabolic "hot-spots", or using the "hot-spots" constructed within the urban development or retrofitting process (Harms and Grimm, 2008); (ii) how to use the local ecohydrological conditions and/or features of the above "hot-spots" to induce or boost their efficiency; (iii) how to integrate them on the city scale in order to manage pollutants and matter fluxes in an efficient way and contribute to system solutions for resilient cities.

2. Materials and methods

This paper uses two case studies of the UNESCO MAB/IHP demonstration network: the cities of Łódź (Poland) and Lyon (France) to show how the concept of ecohydrology has been applied for urban watercourses on different scales, development patterns, strategies for regulating urban sprawl and water systems (Tables 1 and 2 and Fig. 2).

Łódź, with a decreasing population, focuses on an urban retrofitting programme, increasing densification and city

Table 1
Comparison of Łódź and Lyon metropolitan area demographics and urban development models (Lyon: Renard et al., 2010; INSEE; Łódź: Szukalski, 2012).

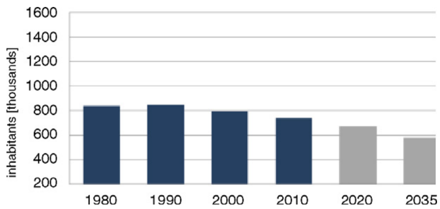
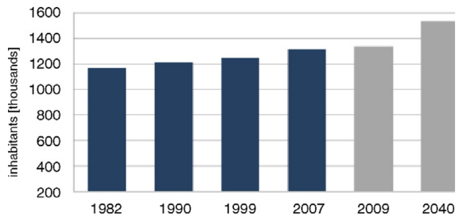
City	Łódź	Great Lyon agglomeration
Historical (dark) and projected (grey) population changes		
Population [inh.]	737,098 (3rd in Poland; 2010)	1,340,155 (2nd in France; 2010)
% change	−7.1% (2000–2010)	+7.3% (1999–2009)
Area [km^2]	293	517
Density [inh./km^2]	2513	2592
Type of urban development	**Agglomeration**	**Agglomeration plus its periurban area**
Population [inh.]	1,116,660 (2010)	1,509,766 (2010)
Area [km^2]	1836	1178
Density [inh./km^2]	608	1291

Table 2
Comparison of natural and urban water resources of Łódź and Lyon; CSO, combined sewer overflows; CSS, combined sewer system; SSS, separate sewage system; WWTP, waste water treatment plant.

	Łódź	Lyon
Rivers network	Dense network of small rivers (18 rivers, mean $Q < 1$ m^3 s^{-1}), channelised and connected to the CSS in the city centre; mostly channelised and supplied with separate stormwater drainage outflows in the suburbs.	Dense network of small rivers (mean $Q < 1$ m^3 s^{-1}), on the west periurban part of the Lyon urban agglomeration. Two main rivers crossing the city (Saône and Rhône). No hydrographic network on the east part (alluvial plains).
Stormwater and sewage systems	City centre: 404.2 km of CSS (~15% of city area; ~42.7 km^2); Outer districts: SSS, including 467.3 km of stormwater drainage (~23% of the city area, ~68 km^2; Suburbs: system of trenches and surface run-offs, directly connected with the streams; Central WWTP (connecting 80% of population), average sewage load: 195,600 m^3/day.	In 2012, the sewer system of Great Lyon is 90% combined with a total length of 2800 km; 11 WWTPs treat 2,237,000 eq. inh. Surface runoff control: 30 rain gauges for real time sewer system control; 5 large detention basins in the eastern part; 360 CSO units (80 in the western part, Yzeron basin).
Water balanced and supply	– min–max monthly air temperature ~ −3 to +30 °C; – precipitation ~547 mm/y; – evapotranspiration ~540 mm/y; – water supply: groundwater + surface water; – mean drinking water use 110 l/cap.	– min–max monthly air temperature ~ −3 to +30 °C; – precipitation ~800 mm/y; – evapotranspiration ~550 mm/y; – water supply: alluvial + ground water; – mean drinking water use: 62.1 l/cap.

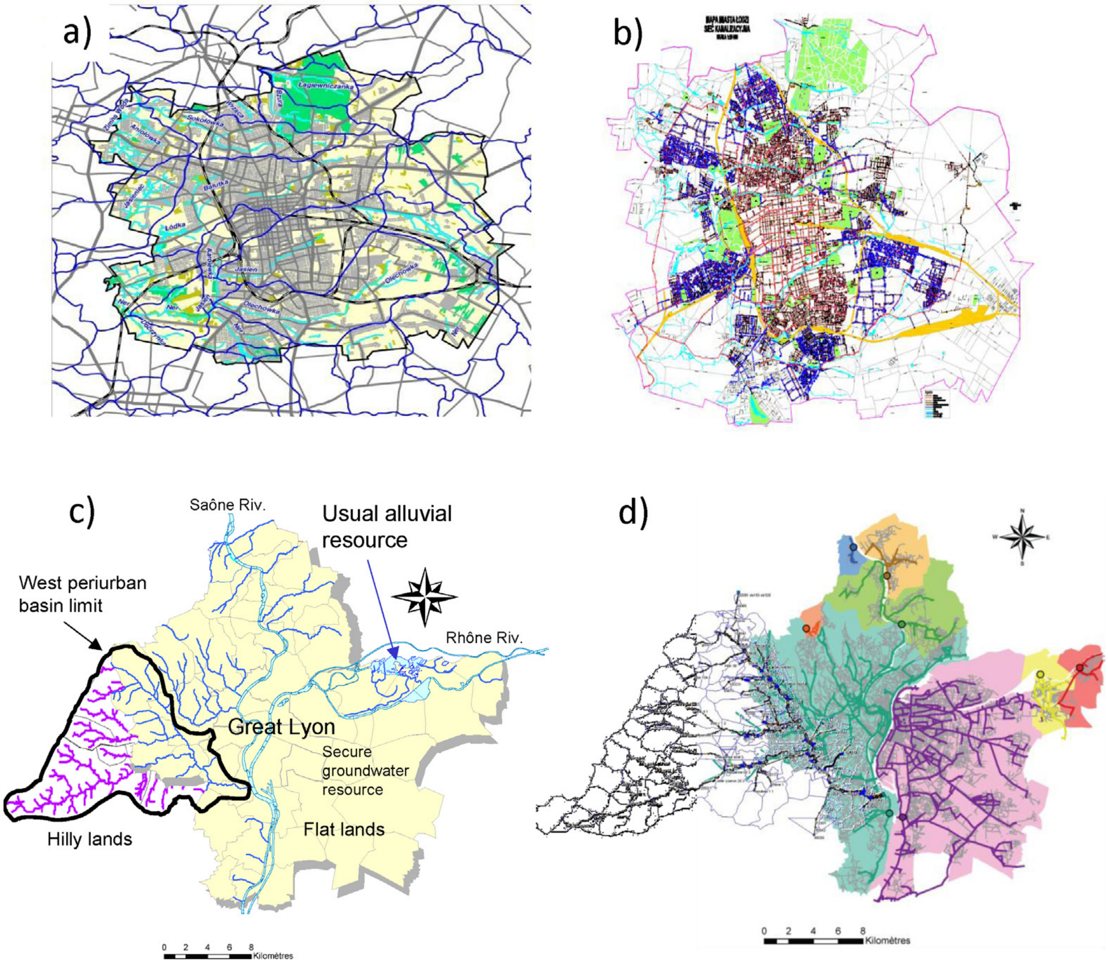


Fig. 2. Natural and urban water resources of Łódź and Lyon; (a) river catchments (blue lines) in Łódź with the Sokołówka river in the north (Wagner, Zalewski, 2009, changed); (b) The sewer network of Łódź covered with a combined sewer system (brown/red lines) and separate stormwater systems (dark blue line), and rivers (light blue lines); (c) Great Lyon boundary in 2006 (grey line) with its hydrographic network (blue lines), the connected Yzeron periurban basin (dark line) and its stream network (purple lines); and (d) Developed sewer network along the main water courses of the Yzeron basin (coloured points are combined sewer overflow devices);.

attractiveness for new enterprises, using water recourses as a core for sustainability. The case study looks at longitudinal stream pollutant dynamics in response to existing urban storm water flows, aiming to identify the hierarchy of drivers for improvement of water quality, and implement them on a demonstration scale. Research was undertaken on a demonstration river, the Sokołówka. The river, with an average flow rate of 0.17 $m^3 s^{-1}$, flows across the northern part of the city and is supplied with about 50 stormwater outlets. It was channelised by concrete stabs, which straightened the course and deepened the bed. The upper catchment holds a dense residential estate of single-family buildings, the middle section is dominated by industrial development and the lower part has maintained a suburban nature, with a significant share of arable land, patches of meadows, wetlands and forests. Most of the catchment area has been sealed with asphalt, concrete, debris or slag, and is characterised by low infiltration. The river is dammed by a cascade of retention ponds, as illustrated and characterised in Fig. 3. The following parameters were measured in the river and the reservoirs in the years 2006–2010: basic nutrients (total phosphorus – TP, and total nitrogen – TN), total suspended matter – TSM, chlorophyll *a*, cyanobacterial toxins (microcystin MC-LR and MC-YR), toxic polychlorinated dibenzo-dioxins and dibenzo-furans congeners (PCDDs/PCDFs – seven 2,3,7,8-substituted PCDDs and ten 2,3,7,8-substituted PCDFs) and heavy metal content (Fig. 3). It also presents key points of the research on the urbanisation impact on the river catchment (Bartnik et al., 2008), and impact of the urban environment and socio-economic status in Łódź on inhabitants health (Kuprys-Lipinska et al., 2009; Rosset et al., 2012).

Lyon, with an increasing number of inhabitants, illustrates periurban development which concentrates the population in urban satellites (villages), providing easy transport connections, and thus mitigating some part of the sprawling negative impact. The study focuses on the evolution of water quality and ecology in time and space along periurban watercourses exposed to urban development. Two sets of data are used: the first set concerns water quality data collected at 23 sampling sites from 1999 to 2006, while the second set results from a biological data set standardised in a previous study (Breil et al., 2010) which had been collected at 103 sites in the stream between 1950 and 2007. According to French normalised methods (SEQ-EAU, 2003) water quality or ecological quality data was ranked into five classes from very bad to very good as to help in the interpretation. To check the difference between pre- and post-urbanisation process in the periurban basin, a two sample *t*-test was used. An experiment aimed at enhancing the self-purification capacity of a very sensitive stream reach to pollution is also presented. Water quality data are collected weekly over 6 months at three locations in the natural and artificial stream bed at 0.3 m depth. The first site is located upstream of a COS unit, the second and third are placed at the entrance and outlet of a sand filter occupying over 14 m of the whole stream bed. The sand filter is located 20 m downstream from the CSO unit. A qualitative comparison of variations in concentrations of nitrogen forms is presented throughout the period of collection. All water quality measurements were performed by qualified water quality laboratories following standardised protocols.

The cases are analysed using the following three steps:

(i) Diagnosing the anthropogenic drivers and pressures in the urban environment, based on the historical and present status of the urban landscape.
(ii) Identifying and quantifying the ecohydrological relationships driving the urban water cycle and its related systems based on combination of knowledge and expertise of the sites.
(iii) Identifying the possible ecohydrological response and framing it within system solutions by linking with social and economic challenges and opportunities, and indentifying how ecohydrological principles can be turned into pragmatic solutions for urban water managers.

3. Results

3.1. The challenge for Łódź: urban retrofitting based on water resources

3.1.1. Diagnosis

3.1.1.1. Urban sprawl and inner city population decline. The textile industry boom in the 19th century transformed Łódź from a provincial town to a major European manufacturing centre. The population, which peaked at around 848,000 in the 1990s has since decreased as a result of the transformations and depressions in the East European economy which decimated markets for the city's textiles. Today Łódź has about 760,000 inhabitants, and demographic projections forecast a further decrease to about 605,000 in 2030 (Szukalski, 2012). This process is driven by migration, either to other cities, driven by the search for employment opportunities, or to the suburbs, where the upper-middle class look for a better quality of life. As a consequence the city sprawls, while the population in the downtown decreases. Since the 1960s, the population of the central district has halved (−54.4%), which hampers its economic development, social and cultural life and attractiveness. In other districts with a better living environment, the number of inhabitants has increased by 6.3% in some districts to as much as 61.1% in others (Szukalski, 2012).

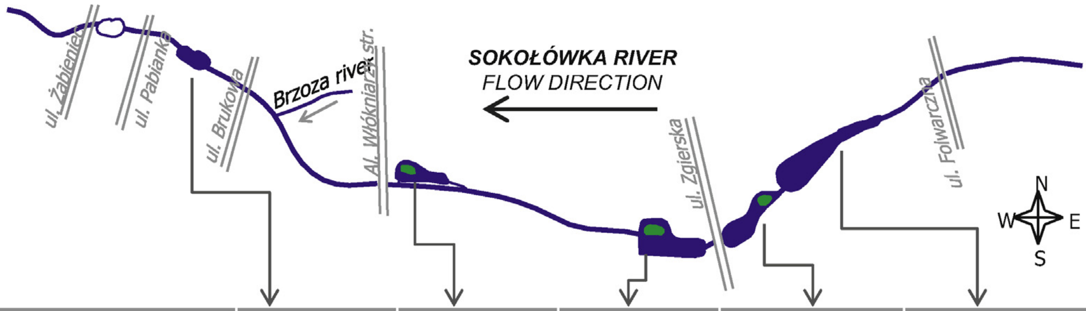
3.1.1.2. Water issues: dense development and degradation of 18 rivers. Rivers were the driving forces behind the economic development of Łódź. The city is located on the watershed divide between the Vistula and Oder rivers, with 18 small stream sources (currently: average flow $< 1\ m^3\ s^{-1}$) within and around the city. Today, in the compact inner city, most of them are channelised, covered underground and included to the combined sewer system. The inefficiency of a stormwater system designed over 100 years ago in current conditions, causes several problems: (i) high risk of local flooding; (ii) severely reduced efficiency of sewage purification by the waste water treatment plant during storm events caused by increased wet-weather runoff; and (iii) urban heat island (UHI): Kłysik and Fortuniak (1999) noted a record temperature difference between central Łódź and its suburbs of 12°. The relative humidity differences between the centre of Łódź and its suburbs typically reach values of 20–30%, with the highest observed difference of 40% (Fortuniak et al., 2006). The water vapour pressure in urban area in winter is usually lower by 1 hPa than in the rural area, while in summer the difference may exceed 5 hPa in extreme cases (Kłysik and Fortuniak, 1999). Despite the relatively small city area, the UHI effect is enhanced due to highly compacted building development, a high percentage of artificial surfaces and the presence of very narrow streets (height/width > 1) in the central section.

In the newer, outer section of the city, the stormwater outlets drain directly to rivers, which in this area, are much less physically degraded compared to the inner city, and possess open, although usually channelised, corridors. High wet-weather runoffs and the relatively high slope of the stream channels (5–7‰) place hydrological stress on the ecosystems of the rivers.

3.1.2. Ecohydrological drivers identification

3.1.2.1. Effect of urbanisation on the catchment scale. Over 70% of the natural sediments within the catchment of the Sokołówka are characterised by high permeability, however, most of them are sealed, as indicated by the high runoff curve number (CN) values (Bartnik et al., 2008). As a result, just within few decades, the Sokołówka has become an intermittent stream, with the unit run off for the whole surface of the catchment not exceeding $0.5\ l^{-1}\ s^{-1}\ km^{-2}$. A comparison of the Sokołówka catchment to another reference catchment located in the region clearly illustrates the effect of urbanisation on existing water circulation: due to much lower retention capacity, the time necessary to reach flood culmination in the Sokołówka is much shorter, i.e. 7 h compared to 20 h for the reference catchment; unit discharges are as much as 3 times higher during the culmination wave than in the reference catchment; the effective precipitation is twice as high as in the reference catchment; and a direct discharge coefficient 1.5–7.6 times greater than that of the reference (Bartnik et al., 2008).

3.1.2.2. Effect of urbanisation on the river scale. These violent hydrological conditions determine the runoff, flushing, downstream transport and seasonal and spatial



STATION	5 PABIANKA	4 TERESA	3 ZGIERSKA	2 LOWER POND	1 UPPER POND
Age in 2013	> 60years	7 years	9 years	> 60years	> 60years
Max. surface area [m^2]	15 000	4 000	18 600	11 000	16 400
Max./average depth [m]	2.0 / 1.3	1.0 / n.a	2.0 / 1.3	1.5 / 1.0	1.5 / 1.0
Capacity [m^3]	20 000	4 100	24 000	11 100	22 500
Average water retention time [days]	3	n.a	8	4	9
Chemical characterisitcs					
TP [mg L^{-1}] (*. 1)	0.29 (n.d.– 0.77)	0.32 (0.08 – 1.64)	0.37 (n.d – 3.50)	0.36 (n.d – 2.65)	0.43 (n.d - 5.53)
TN [mg L^{-1}] (*. 1)	2.6 (0.4 – 11.8)	2.3 (0.4 – 10.6)	2.2 (0.1 – 16.1)	2.4 (0.3 – 14.6)	2.9 (0.4 – 18.9)
TSM [mg L^{-1}] (**. 2)	24.81 (±12.29)	16.73 (±17.99)	9.18 (±5.39)	16.95 (±11.23)	30.74 (±48.94)
Chlorophyll a [mg L^{-1}] (*. 1)	56.8 (1.1 - 245.4)	67.0 (1.0 - 1031.7)	28.5 (1.6 - 95.8)	42.1 (1.0 - 202.2)	60.5 (2.6 - 258.2)
Microcystins [µg L^{-1}] (***. 3)	0.67 (0 – 3.88)	18.72 (0 – 99.62)	0.72 (0 – 2.45)	0.02 (0 – 0.29)	0
Sum of 17 PCDDs/PCDFs [pg L^{-1}] (**** 4)	1327.94	28.36	16.78	23.46	2.04
TEQ [pg TEQ L^{-1}] (**** 4)	60.37	0.009	0.005	0.004	0.004

Fig. 3. Location and characteristics of the reservoirs in the Sokołówka river cascade (technical data: Kujawa, Kujawa 2003) and changes in concentrations of selected chemical parameters. TP, total phosphorus; TN, total nitrogen; TSM, total suspended matter; PCDDS/PCDFs, polychlorinated dibenzo-dioxins and dibenzo-furans. DATA: years: *2006–2008; **2006; ***summer 2008; ****28.01.2008.
Data sources: (1) Wagner et al. (2007); (2) Skowron and Wojtczak (unpublished data); (3) Jurczak and Okyere (unpublished data); (4) Urbaniak et al., 2012; data presentation: average (min–max) or: average (±standard deviation); n.d., not detected.

distribution of various forms of pollutants. The obtained results show various patterns of concentration change with regard to basic nutrients, toxic compounds as well as the effect of the ecosystem eutrophication (Fig. 3).

In case of TP, the concentrations were the highest in the upper, highly urbanised catchment, and decreased downstream, possibly showing lessening impact of catchment and increasing effect of self-purification including the effect of sedimentation in the river–reservoir system. The concentrations were higher in the river than in the reservoirs, reflecting the direct and continuous impacts of stormwater fluxes. In the reservoirs, although the concentrations were insignificantly lower than in a river, they were found to considerably exceed the threshold values for eutrophication (0.1 mg P/l and 1.5 mg N/l; OECD, 1983).

PCDDs/PCDFs and their toxic equivalent (TEQ) showed an adverse distribution pattern with nutrient concentrations and were generally increasing downstream, with higher concentrations in the reservoirs than in the river (Urbaniak et al., 2012). By far the highest concentrations were found in the furthest downstream, and the oldest, reservoir. The results indicate the trapping role of reservoirs and the prevailing cumulative character of the PCDDs/PCDFs transport processes. Intense rains and high flows play a major role in PCDDs/PCDFs redistribution along the cascade by flushing the deposits from the catchment and resuspending river deposits. Increasing the contribution of resuspended fine grain sediments increases the concentrations of associated PCDDs and PCDFs (Urbaniak et al., 2009, 2012).

The distribution of the total suspended matter (TSM) and eutrophication effects (concentrations of chlorophyll *a* and cyanobacterial toxins) depends mostly on the hydrodynamics of the reservoirs, and hence, do not have an upstream or downstream trend. TSM concentration in the river was mainly determined by its discharge, and was found to be 4.5 times higher during storm events than the annual average. High chlorophyll *a* concentrations confirmed the eutrophic

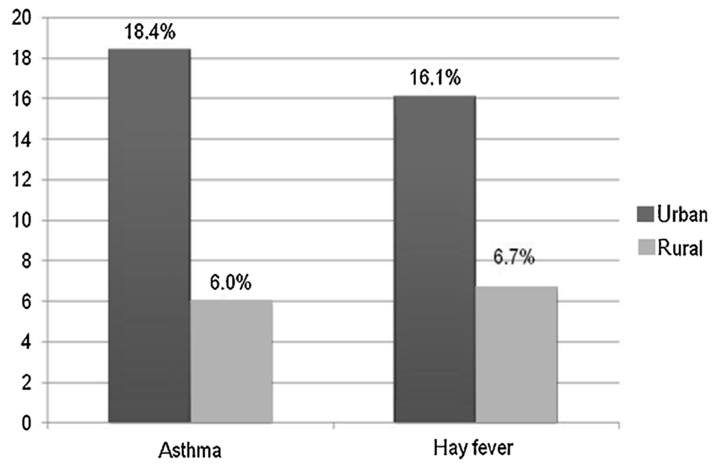


Fig. 4. The prevalence of asthma and seasonal rhinitis in the child population of the Łódzkie Province in the highly compacted Łódź city centre and its greened suburbs (Kuprys-Lipinska et al., 2009).

and hypertrophic character of the system, with concentrations exceeding 25 mg/l (Wagner et al., 2007). The concentrations of cyanobacterial toxins (microcystin MC-LR and MC-YR) observed in three most downstream reservoirs were higher than 1 μg/l (the WHO standard for drinking water; WHO, 1996), and in the final one the values were higher than 20 μg/l (Jurczak and Okyere, unpublished data; standard for recreational waters; Falconer et al., 1999), diminishing the safety of the reservoir for recreational use.

3.1.2.3. Effect of urbanisation on the health of inhabitants on the city scale. Decreased vegetation cover and the presence of an urban heat island are most likely to be the key causes of creating unhealthy urban environment. Allergic diseases and bronchial asthma constitute a key health problem of the contemporary world, especially in areas of dynamic business and economic development. They significantly impair the quality of life, as well as social and occupational activities of patients. The direct and indirect costs of allergy-related treatment are high and represent a significant amount of healthcare revenues (Kupryś and Kuna, 2003). In Łódź, the incidence of asthma was found to be significantly higher in the city centre for both adults and children, as was the incidence of seasonal rhinitis for children (Kuprys-Lipinska et al., 2009), compared to its suburbs, 18 km from the city, with more green space (Fig. 4).

The previous decades have shown that the upper-middle classes are migrating from the central district of Łódź to its districts, either in the outer ring or to the suburbs, looking for a better quality of life. Thus, the diversification of the quality of environmental conditions in Łódź follows the diversification of socio-economic status (SES). Rosset et al. (2012) analysed how environment and related SES (namely: unemployment, education level of the mother and the number of children in the family) can modify the morphological parameters of children. The group of children in the study was diversified in the age, therefore the body measurements standardized using the LMS parameters developed on the basis of a population study of children inhabiting Lodz (Rosset et al., 2009). The results demonstrate that body mass, body height and body

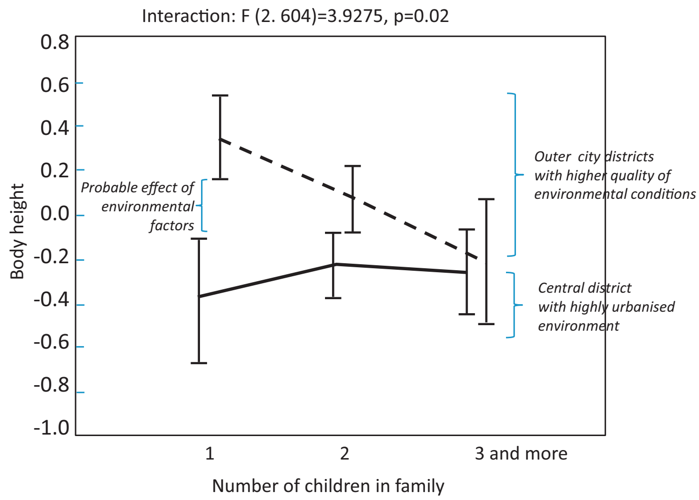


Fig. 5. Comparison of the body height of children in the central district of Łódź, with a highly urbanised environment and associated lower than average socio-economic status (SES) of its inhabitants (spotted line), with the children from a greener section of the city, characterised by higher SES of its inhabitants (solid line; Rosset et al., 2012, changed).

mass index (BMI) are significantly lower in children living in the city centre (Fig. 5). This variability was also significantly modified by the non-specific type of urban environmental conditions. Further analysis is needed to better determine the role of the environmental factors.

3.1.3. Possible ecohydrological response

Reducing the risks related to the above threats requires a reversal of the degradation of the water and biogeochemical cycles in the urban area of Łódź. Achieving this goal in the hydrogeological location of Łódź strictly depends on the ability to increase landscape retention and onsite purification of stormwater. Therefore the identification of ecohydrological feedbacks formed the basis of the development and implementation of a number of measures on the river-catchment-city scale (Table 3).

Ecohydrological measures implemented at the Sokołówka river (Fig. 6) have attempted to harmonise the existing hydrotechnical infrastructure with the potential of its ecosystems to absorb human impact, and to enhance their capacity for absorbing water and pollutant fluxes without compromising the quality and appearance of the ecosystem. The key activities included:

(i) construction of the sequentional stormwater purification system (containing sedimentation, biogeochemical, and constructed wetland zones) in the upper section of the river with the mostly transformed catchment (implemented, patent number: WIPO ST 10/C PL390099). In the first two, experimental years of its operation, the SSPS reduced the concentrations of total nitrogen and phosphorus by up to 60% (Zalewski et al., 2012). Stabilisation of the river flow by constructing a detention basin upstream of the system shell further reduced the stochasticity of the process;

(ii) construction of a cascade of retention reservoirs on the river in order to mitigate extreme flows and hydrological stress. The grey (geocells, gabions, piers, and morphological adaptations) and green (phytotechnology for nutrients removal) infrastructure was designed to increase the capacity of the reservoirs to reduce toxic algal blooms, despite high nutrient loads (implemented);

(iii) elaborating river valley and river channel rehabilitation plans for improving the ecological status of a river, increasing the capacity for water retention in the landscape, groundwater amelioration level, vegetation growth and improving the social access and use of the

Table 3
The key challenges, related research areas and their practical application in the Łódź case study (Wagner and Zalewski, 2011, changed).

Diagnosis/challenge	Research	Research application
Dense urban development of catchments	Hydrological effects of urbanisation on rivers (Bartnik et al., 2008)	Developing water budget and mathematical models for stormwater management in Łódź;
Pollution of city rivers and reservoirs	Effect of hydrological regime on nutrient transport (Wagner et al., 2007) Seasonal and spatial analysis of persistent organic pollutant (POPs) distribution (Urbaniak et al., 2009, 2012) Cyanobacterial blooms and toxins in reservoirs (Jurczak, Okyere, unpublished) Effect of aquatic ecosystem contamination on the condition of fish at molecular level (RNA/DNA ratio; Mankiewicz-Boczek et al., 2010)	Design of sedimentary-biofiltration system for stormwater purification; Assessment of risk for safe recreational use of reservoirs; Improved design of stormwater reservoirs with increased absorbing capacity against pollution based on the EH approach; Indicator for biomonitoring of urban rivers degradation and a screening method for evaluation of contamination of water ecosystems.
River channelisation, aquatic ecosystem and valley degradation	Vegetation mapping and landscape validation of the valley (Kiedrzynski, unpublished); Effect of river degradation on fish communities (Mankiewicz-Boczek et al., 2010; Kruk et al., 2005); Analysis of current and proposed land use within the Sokolowka River Park with respect to local community needs, visions and attitudes (Krauze, unpublished)	Elaboration of a river rehabilitation plan; Elaboration of the river valley rehabilitation plan; Creation of a project for Sokołowka River Park.
High sludge production in the overloaded WWTP	Optimisation of sewage sludge use for fertilising energetic willow plantations for biomass production (Drobniewska, 2008);	Conversion of sewage sludge into energetic willow biomass as an alternative energy source;
Health risk resulting from the urban environment	Impact of urban green areas on the epidemiology of allergic diseases and asthma (Kuprys-Lipinska et al., 2009); Impact of urban environment and socio-economic status of families on the anthropometric parameters of children (Roset et al., 2012)	Creating a basis for a friendly and healthy urban environment – Blue Green Network Concept (Zalewski et al., 2012).
Need for new ways of urban planning	Possibilities for the use of stormwater as a key factor for improving quality of life and revitalisation of the city and its implementation at the level of spatial planning (Wagner and Zalewski, 2009, 2011)	
Institutional barriers	Stakeholder analysis and institutional mapping (Wagner et al., 2010); Defining key socio-economic drivers of water quality in the city and elaboration of their risk profiles (Krauze and Wlodarczyk, 2010)	Building an institutional background for IUWRM, identifying gaps and overlaps in competences, identifying mechanisms for decision-making processes. Building a comprehensive knowledge base on the drivers of water resources; understanding people's attitudes behind the decision-making process, and elaborating priority actions for Łódź water strategy

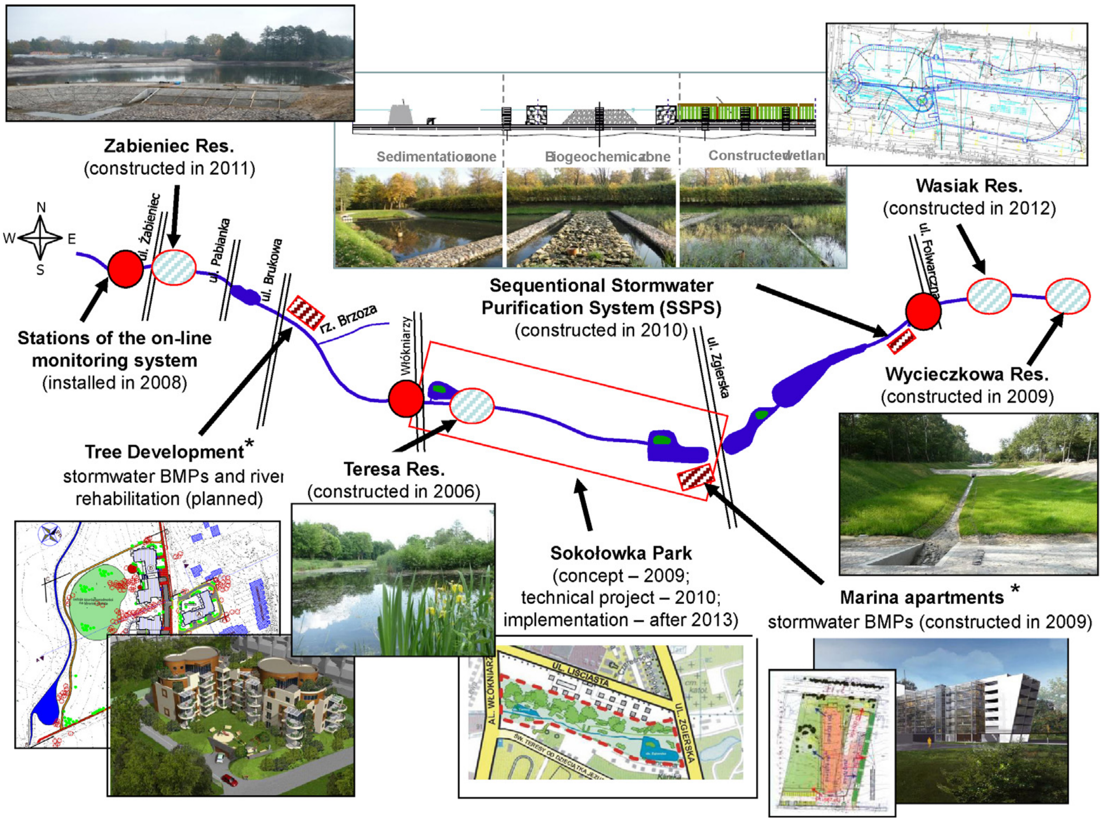


Fig. 6. Interventions linked to the implementation of ecohydrology in urban space in the demonstration project on the Sokolowka River in Łódź. *Implementations resulting from bottom-up initiatives due to the dissemination activities (Wagner and Zalewski, 2009, 2011, changed).

area. The plans were used for elaboration of conceptual and technical projects of a Sokolówka River Park;

The above results enabled up-scaling of the concept to a larger (city) scale:

(iv) elaborating recommendations for the development of all Łódź river valleys, based on a three-zone spatial organisation: ecohydrological regulation, recreational use and low residential development. Such a framework assures necessary space for the rehabilitation and maintaining of ecohydrological processes essential for the functioning of rivers in the urban space without compromising city development (elaborated plan);

(v) elaboration of a Blue–Green Network concept (Fig. 7) based on connecting the river valleys and green spaces of Łódź, increasing the ecological stability of the rehabilitated urban ecosystems and creating a foundation for a friendly city resilient to global climate change. This concept has been included into the Study

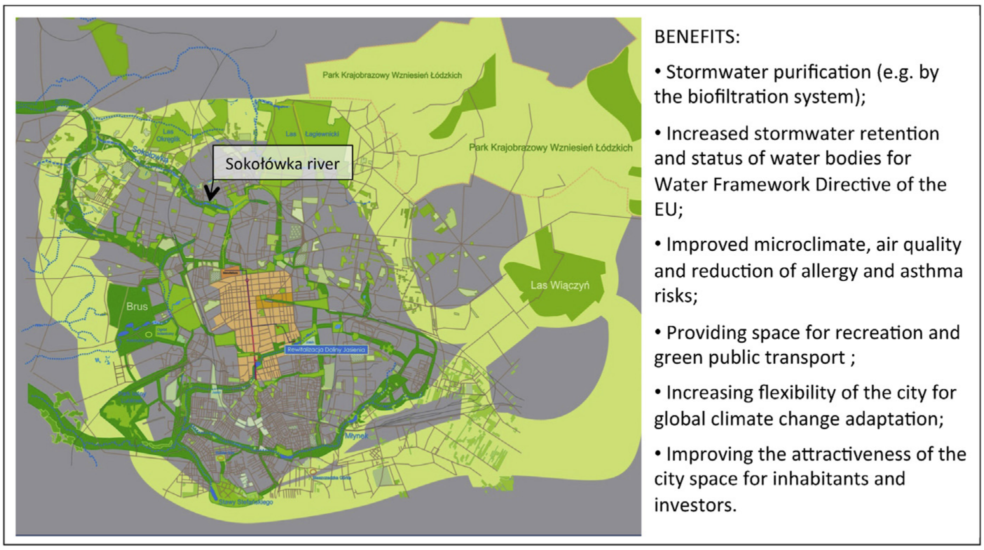


Fig. 7. Blue–Green network: new basis for sustainable and restorative redevelopment of Łódź, and its multidimensional benefits for the city sustainable development (Zalewski et al., 2012).

of Conditions and Directions of Development of the City of Łódź (in 2010), and recently adopted by the City Council as a part of its Strategy for Integrated Development: Łódź 2020+ (operating);

(vi) finally, the implementation of demonstration activities created space and expertise for higher, pre- and post-doctoral education, awareness raising and training, empowered decision-making, fostered inter-institutional cooperation (Wagner et al., 2010, 2011), and triggered several bottom–up initiatives, including the implementation of BMPs in new investments and greater participation of NGOs in further development, promotion and implementation of the Blue–Green Concept.

By following the above activities, the city authorities moved towards restoring the quality of the city through an integrated approach in which rehabilitation of the environmental component of the city and its spatial planning are regarded as just as important as economical and social issues (UML, 2012: Strategy of Integrated Development of the City of Łódź, 2020+). The rehabilitation of green and blue areas in a systematic manner enables recognition and a closer association of the environmental heritage with the revitalisation of the historical industrial architecture of the city.

3.2. Lyon challenge: periurban development in respect to stream ecological quality

3.2.1. Diagnosis

3.2.1.1. Intensive periurban development under uneven hydrographic conditions. Historically founded under the Roman Empire, Lugdunum (Lyon) was erected at the confluence of Saône and Rhône rivers. The city spreads over a flat alluvial land on the east and south and diffuses along valleys and crests on the west hilly land. The hydrographic network on the east of the city is very underdeveloped compared to its western side (Table 2 and Fig. 2). In 2009, the agglomeration of Great Lyon area, with its 58 municipalities, was inhabited by around 1.28 M inh. The urban area, which includes a number of periurban villages, increased from 1.35 to 1.51 M inh. between 1999 and 2007. The increase in population over this period was 11.9%, half of which (6.5%) could be attributed to urban expansion, including part of the periurban area, and half (5.4%) to urban densification (data from the French National Institute for Statistics and Economical Studies – INSEE, 2010). From 1999 to 2005 (Fig. 8a) the rate of densification was greater in the periurban area all around Great Lyon than within the Lyon district itself. Interestingly this indicates that suburbs are progressing slower than the rest of the urban area. Moreover, a foresight population study conducted in the Rhône-Alpes Region (Fig. 8b), predicts population growth to be greater in the peri-urban area of Lyon, which presents new challenges in terms of habitat development.

Moreover, several studies linked to the recurrent national population survey confirm (Espinasse, 2007; Geay, 2011) the presence of an evident social gradient from the centre of Lyon to periurban areas, with a dominant young and active population in the centre, a retired population in the suburbs with better access to facilities, small buildings and houses, and a population of families owning houses with gardens in the outskirts of the city. These social categories have expectations that clearly influence the

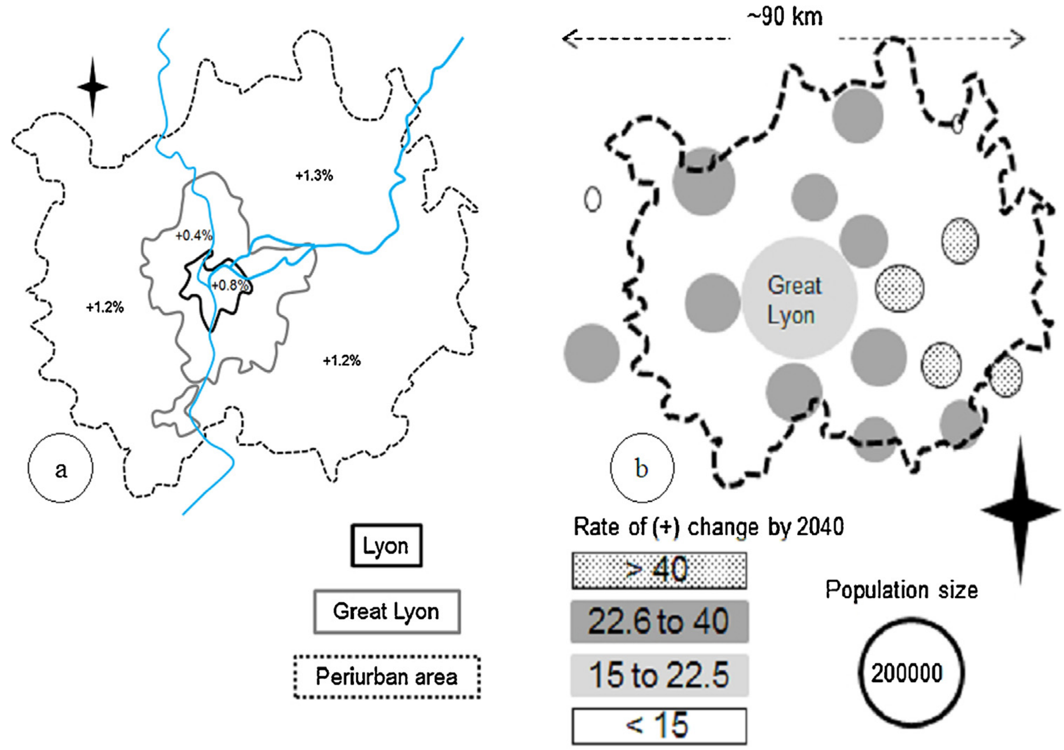


Fig. 8. (a) Mean rate of change in population over the period from 1999 to 2005. Periurban areas exhibit 1.2% vs 0.4% in the sub-urban areas and 0.8% in the centre (Espinasse, 2007) and (b) total rate of change expected by 2040 is greater in the periurban area of Lyon then in Great Lyon itself (Geay, 2011).

pattern of urban development: for example, although an efficient transportation network is required between the city centre and its periurban areas, these areas are not currently the responsibility of the Great Lyon authority (Espinasse, 2007). Long term commitments are then required between Great Lyon and the periurban districts to ensure coherent and sustainable win-win development.

The case study presented here focuses on the west part of Lyon drained by the Yzeron stream, which flows for 20 km from 917 m to 162 m (a.s.l.) before reaching the River Rhône at Oullins, a southern district of Great Lyon. Its basin, with an area of 150 km^2, presents a gradient of land uses from forested in areas far from the city and elevated parts, through a mix of farming, cultivated lands, grasslands and villages in the middle, and progressively to a more dense urban fabric penetrating into Lyon. This basin exhibits fast periurban growth, as seen in population surveys, propagating from a flat urban historical centre towards steeper rural areas. Since the seventies, land conversion has been clearly evident, resulting in a recession of farming activity, with part of the lands returning to forest, but mainly being claimed for the benefit of urban settlements. This is well illustrated in Table 4, which details the four main land uses for the 1970s and the 1990s. A comparison of the upper basin and the whole basin clearly shows that the urban proportion of change in the periurban land category is greater in the upper basin, while the urban change dominates in the basin downstream.

The Yzeron stream flows across granitic and gneissic geological formations that are progressively covered downstream by glacial and fluvial foothills. Steep-sided and local aquifers develop in narrow entrenched valleys into colluvial and alluvial deposits of gravel and sand. The basin water resource is then limited by and closely connected to the rainfall regime. Human activities then depend on an imported water supply from Great Lyon for irrigation and domestic uses (Breil et al., 2008). Almost 90% of waste water produced in the Yzeron basin is connected to a combined sewer network flowing to a central waste water treatment plant operated by Great Lyon. This again demonstrates how water is a challenge in the periurban development. Technical solutions adopted to manage the urban runoff differ between the east-flat and west-steep lands at each side of the city. To the east, detention and infiltration basins are used to infiltrate water in the soil because gravity flow is not efficient. To the west, stormwater flow into receiving streams and seasonal tributaries by the way of combined sewer overflow devices at many points.

3.2.1.2. Water related issues and challenges in the periurban Yzeron basin. As the result of intensive periurban development, numerous combined sewer overflow units are present (Table 2 and Fig. 2) to secure habitations and roads from inundations that could occur during medium to intense rainfalls. This explains why the Yzeron natural network receives so much pollution. Combined sewer overflows are now widely recognised to impact receiving aquatic ecosystems in the Yzeron basin. Another problem comes from the degradation of the sewer network over time. In the case of Yzeron, it was built in the 1970s, and now presents numerous sealing defects. The consequence is the drainage of the already limited ground water resource. The drainage effect was calculated to leave only 10% of the natural water in the stream during the low flow period (Breil et al., 2010). Mean interannual discharge of the low flow period was also found to decrease along the Yzeron stream at gauge stations located in rural and densely populated urban landscapes 12 km and 18 km from the source respectively (Braud et al., 2013). This is not surprising knowing that main sewer pipes run along the Yzeron stream to ensure an efficient flow under gravity. This resource withdrawal by the sewer network results in a serious problem for the functioning of the Yzeron stream ecosystem and moreover, reduces the dilution capacity of the stream during the dry season. This represents a major problem in such a naturally limited water resource as it can hamper efforts to improve the situation. The main courses in the upper and middle part of the basin (water mass number 482a) have been designated to reach a good ecological status by 2015 (Fig. 9). However, in the lower and most urbanised part, which is considered as a heavily modified water mass (482b), the "good ecological potential" objective to reach by 2021 is yet to be defined (Breil et al., 2009). It should be based on a balance between supporting economical efforts and improving the ecological quality and ecological services the expected improvement would provide.

This diagnosis briefly outlines urban development and states that related infrastructures play, and will continue to play, a major role both in terms of threats and possibly opportunities for the Yzeron water resource in the coming decades. A basin scale assessment of the capacity of the stream ecosystem to transform nutrients delivered by combined sewer overflows would help to guide initiatives to rehabilitate and protect the main water courses of the Yzeron.

3.2.2. Ecohydrological drivers identification

3.2.2.1. Global water quality assessment. An analysis of water quality and micro-invertebrate composition was performed based on data collected since 1999–2006 at 23

Table 4
Percentage of land use changes over 38 years in the Yzeron basin.

	Land use for upper basin (50 km^2)			Land use for near whole basin (130 km^2)		
	1970	1990	Change	1970	1990	Change
Forest	37	44	8	23	28	5
Farming and grassland	50	19	−31	50	18	−32
Periurban	2	18	16	7	19	12
Urban	11	20	9	20	35	15

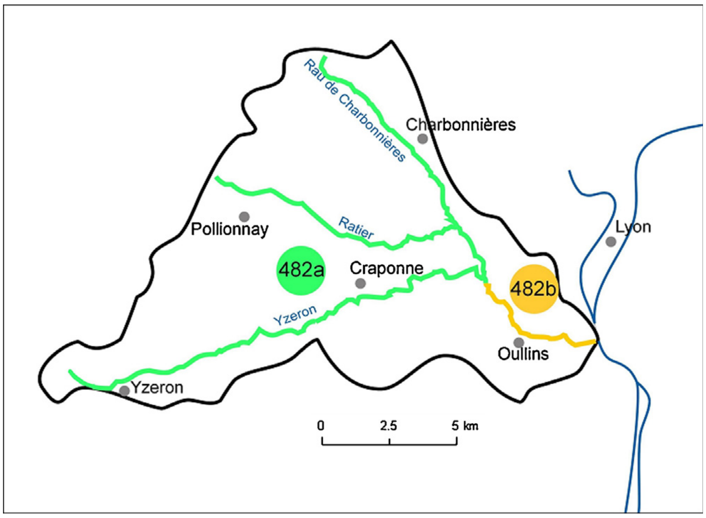


Fig. 9. The two water masses 482a and 482b identified in the Yzeron basin to set ecological status objectives. 482a is assigned a good ecological status by 2015 and 482b a good ecological potential by 2021.

sites along the two main water courses of the Yzeron basin. The diagnosis (Sagyrc, 2007) provided a view of the general water quality status in the 1990s. The data was standardised in accordance with the French normalised method (SEQ-EAU, 2003) and sampling stations were given a score that was generalised to stream reaches by experts (Fig. 10). Very good quality was observed upstream of the two main water courses, as was expected in less developed areas, with a general decrease downstream, where dense urbanisation takes place. However it was also noticeable the quality could improve in some intermediate reaches despite the increasing number of combined sewer units going downstream.

This could indicate that these streams possess a natural self-purification capacity that would play an important role in the resilience of the Yzeron with regard to ecological quality. However, to best decide the future of water masses 482a and 482b, this possibility should first be well understood. A transdisciplinary study incorporating elements of hydrology, geomorphology, hydrogeology and hydrobiology, as well as testing the chemical profile of the water, was then conducted between 2009 and 2010 (Breil et al., 2010)

3.2.2.2. Are there key sectors for water quality regeneration along the Yzeron stream?. To evaluate effect of urban development on the general water quality over time, 103 samples of aquatic biota (invertebrates) and water quality parameters collected over the period from 1950 to 2007 were gathered (Breil et al., 2010). The samples were obtained from 37 sampling sites distributed along the two main watcourses of the Yzeron basin (Fig. 10, red dots). A normalised global biological index (AFNOR, 2004) based on species diversity and abundance of benthic fauna was used to compare results between sites. The index scores range from 0 (very polluted) to 20 (very good water quality).

Considering that the most important land use change was due to the urban development which took place

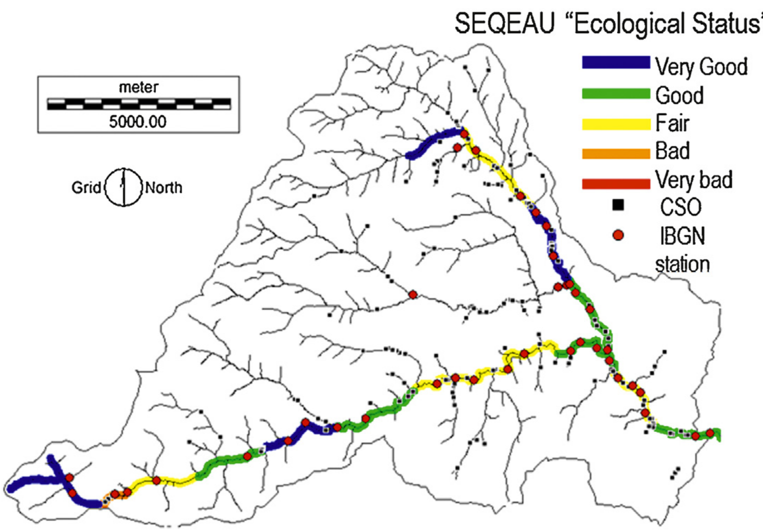


Fig. 10. Global water quality status categories on 1999–2006 (French method SEQEAU) along the Yzeron basin main streams (see colour legend). Location of combined sewer overflow units (black squares) and of biotic indicators sampling sites (red circles).

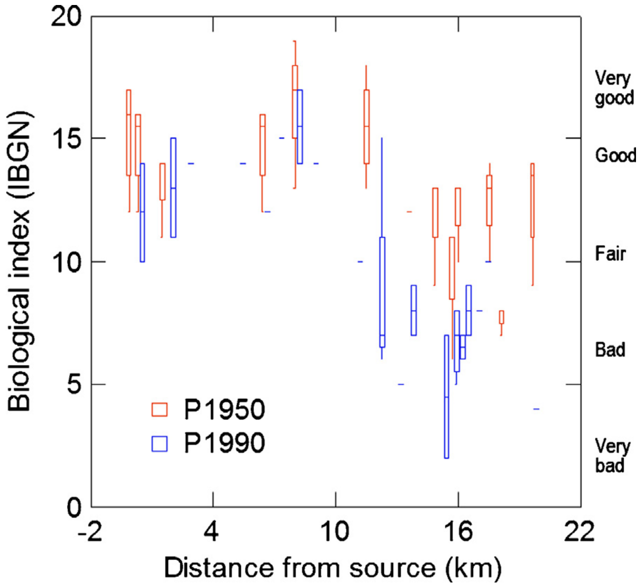


Fig. 11. Box-and-whisker plot of IBGN values from source to mouth for the Yzeron stream. Data are pooled in two samples with P1950 for data from 1950 to 1959 and P1990 for data from 1992 to 2007. Quartiles, median and whiskers corresponding to min. and .max values in the range of 1.5 inter quartiles.

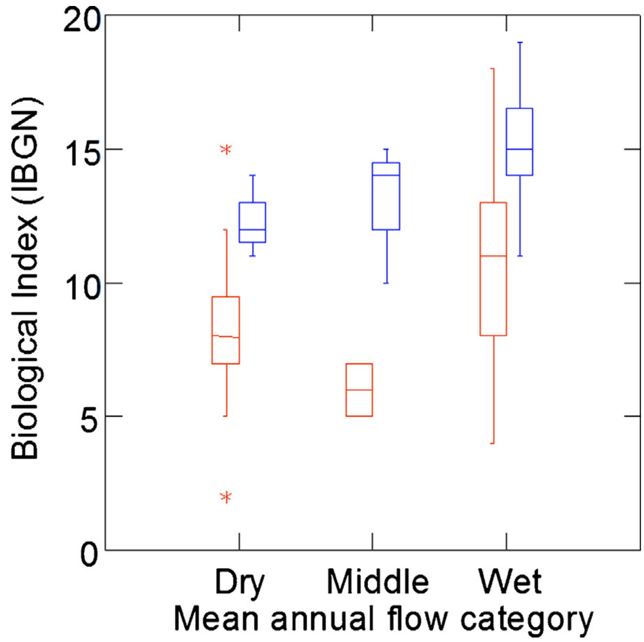


Fig. 12. Box-and-whisker plot of IBGN values to figure the effect of the Yzeron mean yearly flow on IBGN values. Periurban and urban data. Quartiles, median and whiskers corresponding to min. and .max values in the range of 1.5 inter quartiles range. Stars for data value in the range of 1.5- to 3-folds inter quartiles range.

between the seventies and the nineties (Table 4), the results were pooled in two groups: P1950 (1950–1959) and P1990 (1992–2007). Fig. 11 illustrates how median (50%) and interquartile (25% and 75%) values globally decrease from source to outlet along the Yzeron main water course for the two periods. This observation indicates that pollution pressure has existed downstream since the 1950s which is in accord with the urban and industrial development period of this part of the Yzeron basin in the early XXth century. However it is also noticeable that biotic index score for the P1990 samples decreases more dramatically downstream, where a sensitive development occurred in the last decades. Knowing that this significant urban development exists 10 km downstream from the source, a two samples *t*-test was performed between the P1950 and P1990 data located upstream and downstream of this point. The comparison revealed that while the difference between the mean values in the upper basin is weak ($P = 0.723$), it is highly significant in the downstream part ($P = 0.000$).

This result suggests the upstream basin has remained in good health since 1950 despite the observed periurban and urban developments. Moreover these results (Fig. 11) confirm that the water quality regeneration capacity detected in some reaches of the Yzeron stream is resilient to the existing evolution of the landscape (Fig. 8).

Also noticeable is the discrepancy between the "good" global water quality score observed downstream (Fig. 10) and the "fair to bad" quality scores given by invertebrate analyses (Fig. 11) in the same place but including longer record periods. Water quality measurements are, in fact, very dependent on the time of sampling and cannot generally represent the transient effect of combined sewers which occurs during storm events. Of more interest is the sensitivity of biotic material to the flow regime. To test for these effects, years were ranked into three flow regime categories: dry, middle and wet, depending on the rank of their lower mean monthly flow. The results shown in Fig. 12 reveal an improving trend with more water in the upper basin part, which makes sense, considering that many tributaries will dry up during a dry year. In the downstream basin, a significant minimum for middle flow regime conditions can be found for biotic response. This can result from the fact that CSOs are less active during dry years, and that dilution and cleaning effects protect biota from the impact of CSOs pollution during wet years. Hence, the years with middle flow conditions seem to be the least favourable. From the perspective of global climate change, longer dry periods with more intense rainfalls are expected, which may well create adverse conditions for biota.

3.2.3. Possible ecohydrological response

In this study, sectors of water quality regeneration were found to remain stable over time, while more sensitive sectors exhibited a decline of the quality of both their water and invertebrate biota together with the increasing pressure accompanying urban development. A deeper analysis of local conditions reveals that drivers of this spatial heterogeneity relate to pervious substrates such as grabble and sand, allowing water exchanges with groundwater through the hyporehic zone. This interface between surface water and groundwater has received a great deal of research interest (e.g., Breil et al., 2007a,b; Grimm and Fischer, 1984; Marmonier et al., 2012; Naegeli and Uehlinger, 1997), the results of which confirm that it constitutes a main bio-processing layer in a running freshwater ecosystem when present. For part of its course, the Yzeron stream flows over rocky outcrops on which no biotic process can take place. Any pollution input then propagates about several hundred of metres downstream. In these stream sections, CSOs should be avoided, which in turn can help set priorities in the rehabilitation strategy and emphasise the need to avoid any polluted outflow in these sensitive stream sections in future developments. This knowledge has been used in two ways:

(i) First to help stakeholders prioritise their efforts with regard to the combination of CSOs units and the self-purification capacity of stream sections. The results are presented for the entire Yzeron stream network in Fig. 13. Reaches are ranked into categories of filtering capacity for the sake of clarity. The substrate filtering category corresponds to a stream running fairly straight along a bottom gradient of 1–3%. Stream meandering is a natural adaptation of a stream with a rock bottom as long as it is fed with enough material from upstream and the general bottom gradient is low enough. Meandering occurs in some parts of the Yzeron stream network creating opportunities for bank filtering, the second category given in Fig. 13. Optimal metabolic effect is expected from the combination the features of the two previous categories. Category four with no effect corresponds to an urban stream with a concrete bed. No filtering is expected from head waters, where the dominant grain size is of some centimetres with bottom gradients of more than 3%, reaching as high as 10%. However, they do exhibit a self-purification capacity by the way of important aeration caused by cascade successions.

In terms of operational issues, in pollution-sensitive sections with category two filtering capacity, CSOs should be limited by controlling surface run-off at source or treating pollution using planted filters before the overflowed water reaches the stream. If not possible due to limited space or budget, an alternative is to enhance the in-stream self-purification capacity to limit the propagation of pollution downstream. In the case of regeneration sections, as observed in Fig. 10, particular attention should be given to their local protection against such new pressures as ground water extraction or intensive agriculture practices.

The other sections present an intermediate capacity to manage bio-degradable pollution. They vary with the flow regime over time (Fig. 12). They should correctly process uncontrolled CSOs most of the time but eco-technological assistance would locally enhance their self-purification capacity and the overall resilience of the stream system to urban development.

(ii) Second to develop an experiment aiming at increase the bio-degradation capacity of a seasonal creek exposed to a CSO unit. The experiment consists in a 14 m long sand filter that was obtained by natural filling with floods after a barrier of 1 m height from the creek bottom was build. The bottom is made of granite with a very limited infiltration capacity. The barrier is made of wood staved-in the banks of the creek but is not sealed to allow water to seep through the barrier when the flow discharge is low. The filter structure is positioned 25 m downstream a main CSO unit. The objective of the sand filter is to intercept combined sewer overflows happening during the low flow period when no dilution capacity exists. This system takes place in a sensitive reach where a critical situation was detected (Fig. 13), where low dilution capacity and bedrock outcrops dominate, meaning an overall restricted ecological buffering capacity. Nitrogen forms are presented in Fig. 14.

First it was observed from the water level in the wells that the ground water was flowing downstream along the sand filter, meaning from S1 to S2, even with no perennial surface flow during the dry season. Now looking at the dominant nitrogen forms, ammonia and nitrate, it is observed that in S0, upstream the CSO unit, nitrate form

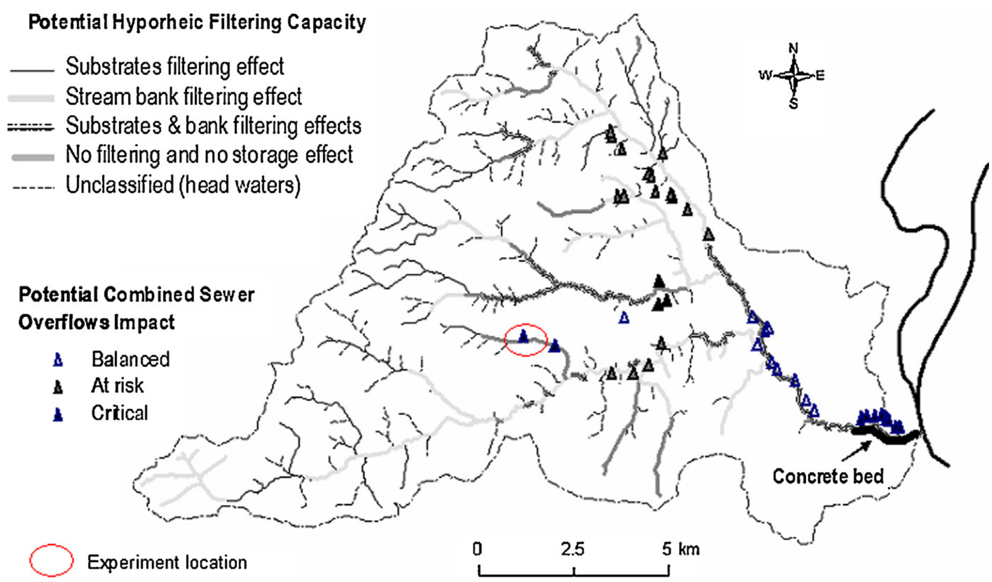


Fig. 13. Setting of priority for CSO unit best location and management adaptation regarding at the potential self-purification capacity of receiving stream sections. Adapted from Breil et al. (2008).

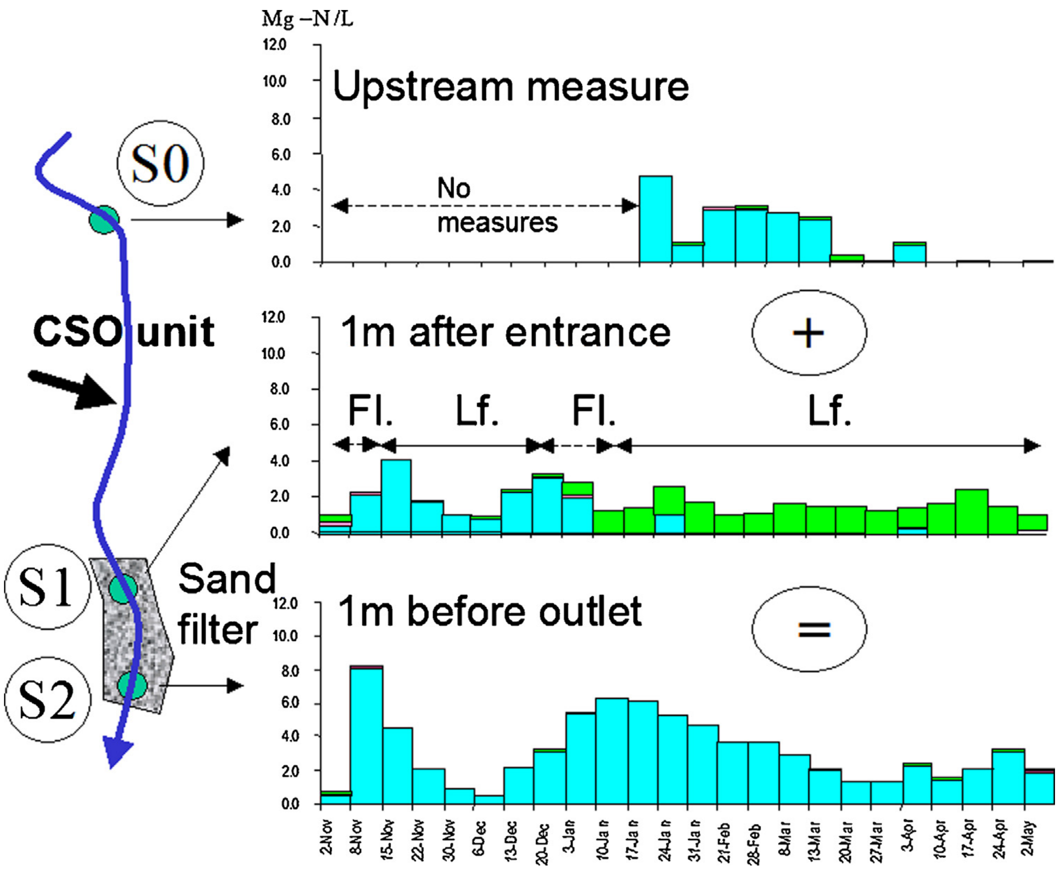


Fig. 14. Evolution for nitrate (blue bars) and ammonia (green bars) concentrations with time and space in a sand filter placed just downstream a CSO unit. S0, S1 and S2 are sampling sites from wells dug in the stream and sand substrates. Lf: low flow period; Fl.: flood period. See experiment location in Fig. 13. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

dominates in the natural sandy porous matrix. Conversely in S1, located in first metres of the sand filter, ammonia dominates during the same dry period. This nitrogen form is a poison for aquatic small species and it comes with CSOs events. It is observed that in S2, there is no more ammonia but mineral nitrogen which concentration is in accordance with its potential source, meaning ammonia entering the filter. These data show how it is possible to increase the local bio-degradation potential given the natural limitation of a creek reach.

The study developed on the Yzeron periurban basin reveals that a stream system can present various capacities for self-purification along its course. There are naturally regeneration sections or "hot metabolic spots", sections with metabolic potential that could be boosted using ecohydrological techniques and sections sensitive to pollution. This information should be considered when planning the urban development and sewer system outlets in particular. A better knowledge of the spatial distribution of the metabolism of the stream is the first step, and an argument for the implementation of ecohydrological solutions at full basin scale and with a long term perspective.

The periurban area is often located upstream of related urban environments, and offers more free space than the dense urban areas. It therefore requires treatment as a strategic sector in order to preserve the water resource and to reduce the risks linked to extreme hydrological values. This should allow a more water-centric and sustainable development of the urban fabric in its watershed.

4. Discussion

4.1. Opportunities for the implementation of functional ecohydrological approaches in urban space

From the perspective of ecohydrology, urbanisation can be seen as a process which transforms natural ecosystems into "*novel ecosystems*" (Hobbs et al., 2006), with new habitat and biotic structures, higher degrees of fragmentation, isolation and area-constraints. Terrestrial ecosystems are fragmented by the city infrastructure such as roads, houses and extended areas of dense development. An example of fragmentation in the flood control urban stream is the bed modification, with at least four levels of ecological degradation (Breil et al., 2008; Poulard et al., 2012), from channelised to concrete channel. Another example is the disruption of river continuity by high concentrations of pollutants due to the presence of sewage from a CSO in amounts unadjusted to the capacity of the ecosystem (Breil et al., 2007a,b).

In such situations, flow paths of energy, water and matter are disrupted and re-directed into unsustainable, human-originated tracks, both within and between the ecosystems. The processes which normally operate continuously in time and space are disrupted. The biochemical cycling is clearly distinct from that known to be the case for unmanaged but mainly agricultural ecosystems (Kaye et al., 2006). The space and time dynamics of hydrology–biota processes are changed. A good example being the ratio of the abiotic/biotic regulation of ecosystem dynamics which, decreases downstream in model, relatively unimpacted systems (Zalewski and Naiman, 1985) and exhibits seasonal pattern in temperate rivers (Wagner and Zalewski, 2011). In urban systems, the regulation of ecological dynamics is dominated by abiotic control, which by principle, diminishes the role of the biotic component in ecosystem quality control.

High impacts and functional changes weaken the resilience of the urban ecosystems (Holling, 1973) and the response to management practices, by diminishing the role of the biotic component, which has great potential to compensate for negative impacts (Zalewski, 2011). From this perspective, two fundamental challenges exist which are related to incorporating ecosystems into the IUWRM: (i) how to shift the current understanding of the role of ecosystems within the IUWRM framework towards a more functional perspective; and (ii) how to assure a satisfactory level of biological performance of ecosystems under high and multiple stress to process the impact without compromising their ecological quality.

In urban rivers, surface water metabolism and absorbing capacity are examples of departing points for addressing their functionality. The stream absorbing capacity both relates to river corridor development, which ensures the processing of lateral nutrient inputs, and to inner geomorphic features which, in combination with the flow and nutrient regimes condition the diversity of its biota and their abundance (Stanford and Ward, 1993). The spatial distribution of such properties is of prime interest when the objective is to use or enhance the natural metabolism. They can be highly dependent on local conditions, and little research has been devoted to this question, particularly regarding the amount of nutrient concentrations and the length of a stretch of stream that can process them without being degraded (Fisher et al., 1998). These spatial properties need to be further elucidated, as well as how these features can be used to set priorities and increase/optimise efficiency of ecosystems in processing nutrients and other pollutants. It has been verified in the two case studies, however, that both the metabolism and absorbing capacity varies along water courses, as well as the drivers of their processing and distribution, as presented in the case of Łódź. The study on the Yzeron periurban basin reveals that a stream system can present variable self-purification capacities along a course of some tens of kilometres. This dimension, with its fragmentation, has received little attention, and self-purification was considered a continuous process from upstream to downstream, based on water quality parameters (e.g. McColl, 1974). The telescoping ecosystem model proposed by Fisher et al. (1998) introduces a dynamic perception of nutrient recycling distance in relation to disturbance regimes and stream corridor lateral connectivity. This model should be of interest in predicting areas of greater self-purification potential without requiring excessive field surveys. Moreover the findings on the role of the hydrogeomorphic template responsible for hot spots and hot moments of carbon and nitrogen cycling in an arid stream (Harms and Grimm, 2008) support our initial results: there are naturally regenerating sections, sections with metabolic potential and sections sensitive to pollution.

Adjustments to physical, biotic and functional properties can be also used for the optimisation of regulatory hydrology–biota relationships in constructed systems. The case of Łódź has shown that distribution of the symptoms of eutrophication, manifested as changes of the biotic structure of ecosystems towards domination of toxic cyanobacteria, and concentrations of cyanobacterial toxins, are dependent more on the hydrodynamics of the reservoir, rather than on its location in the cascade, which is to a certain extent similar to natural systems (Tarczynska et al., 2001). An understanding of these relationships should be addressed already at the stage of the urban reservoirs design, and used for enhancement of their resilience. These aspects need however more researches. Similarly, these rules can be applied for minimising impact on aquatic ecosystems, e.g. different types of constructed wetlands or structural BMPs, such as in the sequentional stormwater purification system in Łódź (Zalewski et al., 2012). Considering the limited space and cost of land, the implementation of such an approach based on enhancing the capacity of the constructed systems would be most relevant in an urban context. The progress could be realised by a combination of ecosystem biotechnologies with technological innovation and existing urban engineering (also hydrotechnical) infrastructure.

Finally, enhancement of absorbing capacity may be considered at a city level. The intensive stormwater-induced water and pollutant fluxes versus the long periods of low flow are examples of two factors which can be stabilised at the catchment level. Source control measures enhanced by a holistic approach to landscape planning process (e.g., the Blue–Green Network), as well as adapting future developments to the capacity of the ecosystem, as shown in the case of Lyon, is therefore fundamental for increasing the absorbing capacity and performance of the stormwater-fed urban aquatic systems. Addressing urban development from the perspective of water resources and integrating opportunities offered by urban retrofitting and periurbanisation, may offer a foundation for more comprehensive (system) solutions directed towards more resilient cities, harmonised with social and economic functions (Zalewski and Wagner, 2005).

4.2. Risks and constraints related to the implementation of ecohydrology in an urban space

Key risks concerned with the implementation of ecohydrology in an urban space refer to the proper adjustments of ecohydrological measures and the possibility of their regulation, as well as proper adjustment (or location) of the technical infrastructure, such as CSOs, to the capacity of urban ecosystems.

By not adjusting management practices (e.g., CSO location) to the ecosystem functions, two possible situations can arise. If the absorbing capacity is underestimated, the key risk relates to over-investing in inadequate infrastructure. However, if pressure is too strong and absorbing capacity of ecosystems is overestimated, the water ecosystem may be degraded, which results in ecological damage, loss of ecosystem services and increased costs of their replacement, as well as a need for the degraded ecosystem to be restored and the relevant measures to be applied. Therefore the most serious risk is associated with the failure of the ecohydrological measures to achieve water quality and ecological status goals. In such a situation, greater investment has to be made towards reduction of the stress input. Natural processes which are the bases for ecohydrological regulation, while being resilient and adaptive, cannot be enhanced beyond certain levels. Processing more stress, by taking a boosting approach, may require increasing the active surface on which the processes take place, which is not always possible.

The possibility to apply ecohydrological, as well as technical, measures changes along the river course in a non-specific manner, as a result of both catchment impact and varying river capacity. Therefore, the type of the solution needs to be carefully adapted to the location resulting from both outstream and instream conditions. Currently, land availability and catchment development (or development plans) are the primary drivers of the location of the hydrotechnical facilities. Basing the choice solely on river absorbing capacity may indicate the most functional location in sections where space is not available. Such a situation may result in either preventing the implementation or compromising quality and functionality of an ecosystem.

Concerning the constraints, urban ecohydrology in its aquatic phase will not be used in the absence of naturally fed aquatic ecosystems. In cities lacking the naturally fed urban water bodies other approaches, such as WSUD, for example, would be a more suitable approach. Some of the ecohydrological regulations can be still used in the urban terrestrial ecosystems, based on adaptations of the experiences gained from non-urban systems (e.g., Baird and Wilby, 1999).

Finally, the city water managers may be further constrained by two other factors. Even though scientific approaches emphasise the importance of the functional aspects of ecosystems, the realities of management and legislation still do not incorporate them. The function of ecosystems is usually restored more as a consequence of the undertaken measures of structural rehabilitation, and is rarely the primary intention. Moreover, ecohydrological solutions should be managed and monitored, as is already the case for water supply, waste water treatment plans and infrastructures. However a methodology for assessing the efficiency of the ecohydrological practices in the urban space, as well as the functionality of ecosystems, is missing. Furthermore, implementation of new systems is always time- and resource-consuming and requires reorganisation of the logistical frameworks.

5. Conclusions

Urban ecohydrology provides an alternative background for city managers to include natural water bodies inside the global urban water cycle. It applies mostly to the natural- or stormwater-fed urban aquatic ecosystems, constructed water systems (e.g., reservoirs, wetlands, sedimentary systems), but also to the terrestrial ecosystems and city scale spatial planning, and can be used for urban water and matter flux control, assuring (storm) water for the city greenery, maintaining air humidity, improving the appeal and economics of the urban space. Until now, the problem was to get a functional view, including metrics, of the natural processes taking place in a natural system under pressure, making the link between urban water related services and its environment (Pickett et al., 2001). Polluted situations occurred from time to time and were considered as a failure in the absence of a means to propose durable and sustainable solutions based on a sound understanding of causes and effects. Failing to include this new dimension in urban water cycle management will restrict the possibility of better stormwater management, instead forcing the manager to rely only on upstream solutions such as WUDS or BMPs. Without a doubt, an understanding of the dynamics of natural processes, including absorbing capacity, metabolic rate, the resultant potential and limits for water, matter and pollutant transformations along the river course, are fundamental for function-focused rehabilitation of urban ecosystems towards:

- augmentation of their resilience to external drivers at global (e.g., climate change), regional (e.g., landscape transformation) and local (e.g., urbanisation) levels and improving their quality; and
- increase their ability to process the fluxes of water, nutrients and pollutants, changing their position in the IURWM from that of impact receiver or rehabilitation object, into the position of the functional element (tool) for management;

Considering that high stress and environmental transformations in urban areas seriously alter structures and processes of ecosystems, influencing the choice of possible management strategies and their results, the following needs to be taken into considerations:

- the applied measures (both ecohydrological and technical, such as CSOs location) need to be well adjusted to human impact as well as to the absorbing capacity and metabolic rate of the ecosystems, in order to avoid ecosystem degradation and ecosystems services disruption. The best management options, depending on both “outstream” and “instream” conditions, can therefore vary even for sections of the same catchment/river.
- ecohydrological measures must harmoniously work together with the existing urban infrastructure, which is usually expanded, rigid and highly complex. Their implementation may require technical adjustment of the existing infrastructure, or its further reinforcing with new technologies;
- a mapping of the stream metabolism seems to be a first necessary step to implementation of ecohydrological solutions on a full basin scale and for a long-term perspective. This water resource dimension should be

considered early in the long-term planning of urban development. It should be included into the appropriation of necessary natural resources when negotiating with authorities of periurban territories. This point is of particular importance considering the projected trend for urban population in many parts of the world, and at the same time the lack of governing instruments addressing this water issue.

Conflict of interest

None declared.

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