Sustainable strategies to treat urban runoff needed

Most cities lack holistic monitoring and green infrastructure to mitigate pollution in urban runoff. We call for systematic characterization of runoff and more widespread treatment to protect biodiversity and human health. This challenge requires data-driven, adapted, low-cost and sustainable solutions for dense urban centres.

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Cities are epicentres for anthropogenic inputs into the environment across the globe. Specifically, urban runoff is a major pathway for pollution to contaminate aquatic ecosystems. As urban areas (mainly composed of impervious surfaces such as asphalt and concrete) increase, so does urban runoff — directly impacting surface water quality and storage[1]. In general, urban runoff is not treated, releasing several million tons of toxic, non-biodegradable and emerging contaminants — including plastic debris, hydrocarbons, detergents, solvents, pathogens, pesticides, heavy metals and engineered nanomaterials — to the environment. In this way, urban runoff is a complex mixture of anthropogenic stressors, some of which can induce acute toxicity to aquatic organisms[2], while others (individually or as a mixture) could present a chronic risk to ecosystems and to humans via seafood and drinking water. Urban runoff mortality syndrome is a well-understood phenomenon that describes mass die-offs in salmon due to untreated stormwater[3]. International actions and policies could be implemented to control pollutant release[4], preventing adverse ecological impacts and long-range transport. Akin to industrial or municipal treated wastewaters, we believe that cities, particularly those surrounded by a small hydrographic network where contaminant dilution is low after discharge into natural waters, should consider allocating more resources to characterize and treat urban runoff. Although several large cities have stormwater best management practices (BMPs) in place, they are mainly designed for water infiltration and/or storage and to address intense rainfall events. They do not target local anthropogenic stressors. Treatment of anthropogenic stressors could occur through the implementation of green infrastructure, such as modular (bio)retention cells, permeable pavements and more advanced sustainable processes. Treatment is particularly critical during intense precipitation events and for sewer systems that combine runoff waters and municipal or industrial wastewater (with overflows being sent to natural waters), or for municipalities with several cross-connected sewers. The local flow-buffering capacity of a stormwater treatment system is critical, with growing concerns regarding flooding associated with global climate change. Yet urban planners and water managers lack reliable tools to design urban stormwater management infrastructure that takes into account both flood and water-quality control. Here we discuss the need for routine characterization of urban runoff and new investments in infrastructure and instrumentation directed towards sustainable and improved stormwater management.

A complex cocktail

The cocktail in urban runoff released to natural waters (~110 billion gallons per year in New York City alone)[5] extends beyond the classical water-quality indicators routinely assessed (for example, total suspended solids, metals, phosphorus and nitrogen). Many other contaminants are released to natural waters via urban stormwater runoff and stormwater sewer systems every day, some of which cause acute toxicity to aquatic organisms (Fig. 1). For example, leachate from tyre rubber (6PPD-quinone) can exceed the acute toxicity threshold concentration in urban streams by more than 20 times[2]. Beyond tyre-wear debris, other plastic-based litter is common in stormwater runoff. In the San Francisco Bay, stormwater runoff is the largest pathway for microplastics[6]. Combined sewer overflow carrying untreated municipal wastewaters also contributes to this load. Moreover, the extensive utilization of single-use personal protective equipment due to the SARS-CoV-2 pandemic (estimated annually at ~15,50 billion masks and 780 billion gloves globally), contributes to the release of plastic litter[7]. Whole masks could reach natural waters via stormwater sewers without any treatment barrier, hence releasing millions of plastic fibres. Several other synthetic wastes, such as cigarette butts (4.5 trillion littered in the environment yearly)[8] and, for combined sewer systems, microfibres from textiles (for example, polyester and acrylic), are also discharged during rainfall events.

Gasoline and oil spills, heavy metals and petroleum-based compounds from asphalt-based surfaces such as rooftops and roads (for example, polycyclic aromatic hydrocarbons (PAHs)) also raise concerns. After a rainfall event, approximately 4,500 ng PAH $\mathrm{l^{-1}}$ was detected in a Colombian river, while some PAHs have a median lethal concentration (LC_{50}) below 2,000 ng $\mathrm{l^{-1}}$ (refs. [9,10]). In some urban areas, fertilizers used for turf maintenance and pesticides or biocides used for parasite control or to protect building surfaces are systematically measured in natural waters (up to 1.8 µg $\mathrm{l^{-1}}$ during peak event)[11]. Persistent per- and polyfluoroalkyl substances present in paper, textiles, flame retardants, pesticides and oils could also be released in natural waters (up to 850 ng $\mathrm{l^{-1}}$)[12]. Finally, engineered nanomaterials can be released from outdoor surface coatings such as paints and stains.

Several other anthropogenic contaminants are released to natural waters after intense precipitation events; many of which are overlooked, such as salts and de-icing chemicals applied in winter, solvents and detergents (for example, windshield washer), and brominated flame retardants. Others are simply unknown. Moreover, the large populations of city-acclimated and domestic animals (for example, mustelids, birds, skunks, raccoons, squirrels and cats) could contribute to the release of pathogens, organic phosphorus and nitrogen (that is, urea) in natural waters.

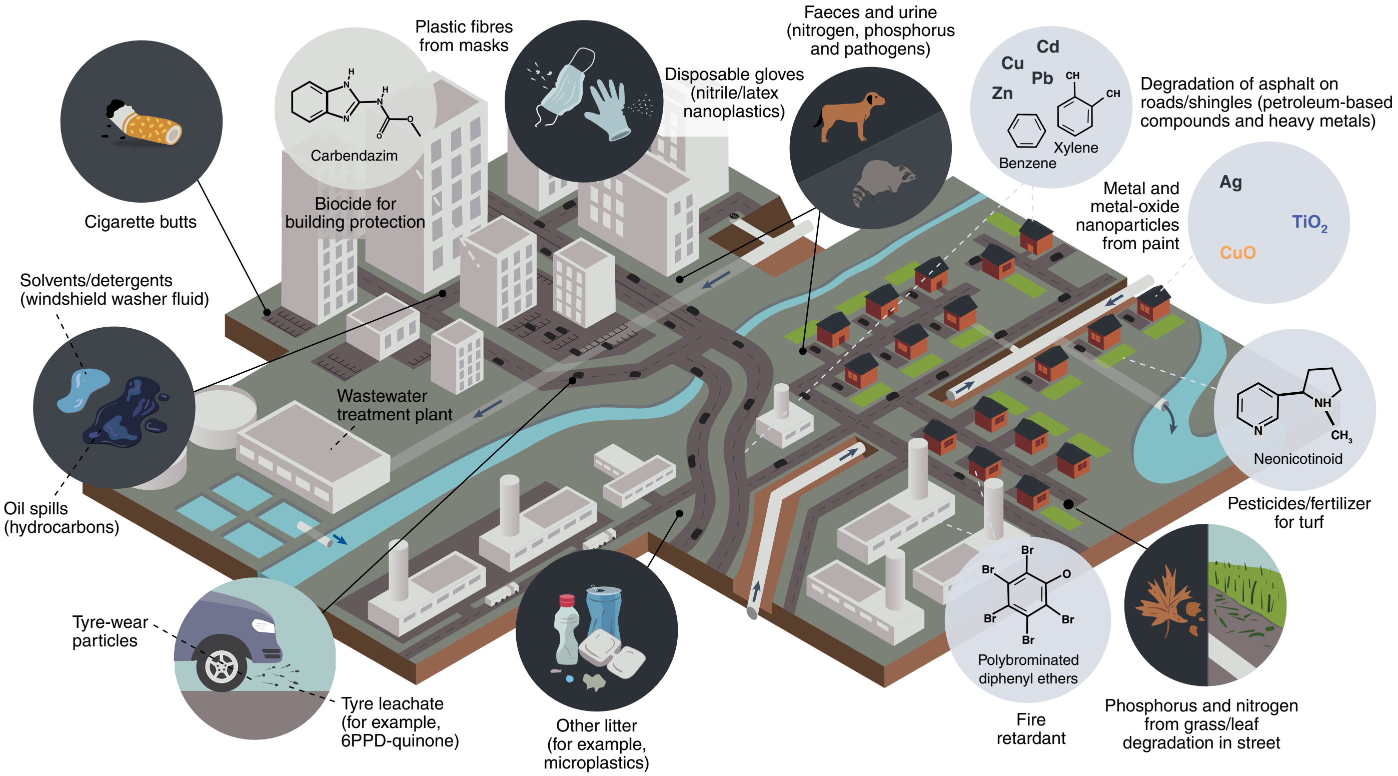

Fig. 1 | Mapping global anthropogenic pressures from conventional and emerging contaminants. Runoffs are not treated. Credit: Audrey Desaulniers (Orceine).

A need for improved characterization

Importantly, the concentrations of these contaminants are not systematically measured, while their combined toxicity effects are ill-defined and potentially underestimated. A better understanding of the loadings of contaminants and any relevant toxicity is crucial to evaluate the risk to aquatic ecosystems and determine sites where mitigation strategies are needed. New innovative low-cost solutions are needed to monitor target contaminants, while simple indicators such as turbidity might be useful to estimate the load of colloidal contaminants (for example, microplastics)[13]. Moreover, whole effluent toxicity testing could be used to determine when urban runoff is a threat. Where toxicity is determined, effect-directed chemical analysis can be implemented to identify chemicals for future targeting. Furthermore, BMPs can be put in place to mitigate the pollution. This procedure can inform both hotspots for toxicity (and thus mitigation) and a targeted suite of chemicals to be monitored and/or regulated. The proposed monitoring of water quality could be combined with existing quantitative tools to monitor flow (for example, online turbidimeter combined with flowmeter). Strategically localized dual systems that are able to quantitatively and qualitatively monitor runoff could be more common in cities (in larger sewers) to better evaluate risk. Monitoring that is designed to provide information about both contamination and risk is crucial for governments and scientists to establish whether more active management is needed and whether urban runoff should be treated before being released into the environment.

Call for sustainable solutions

To simultaneously consider the complexity of hydrology (that is, the impact of rainfall intensity and local topography, which influence flooding) and water quality, urban runoff storage and treatment processes should be more common, especially for densely populated cities where natural landscape is insufficiently available to process, infiltrate and treat stormwater. New and strategically geolocalized infiltration areas, collection systems and/or modular treatment processes that provide certain flexibility for expansion can help mitigate floods and the load of contaminants during peak rainfall or snowmelt events. Large-scale viable and sustainable solutions are needed to store and passively treat urban runoff and deal with intense rainfall events that cannot be hydraulically supported by existing wastewater treatment plants designed to treat lower flow rates. Examples of such existing solutions, as well as more sustainable solutions to be adapted for runoff treatment, include retention ponds, bioretention cells or raingardens (~95% particle removal), coarse sand filters, bio-assisted aggregation and filtration systems, aerated ponds, underground tanks in dense urban areas, adsorption via functionalized media in a granular filter, passive aggregation and settling tanks and passive O_2/ultraviolet (photo)oxidation. Such retention processes could act as onsite surge tanks while also removing several contaminants from runoff, combined sewer overflow, or cross-connected sewers before discharge into natural waters.

Examples of existing and new promising solutions are presented in Fig. 2 and include hydraulic buffers (solutions 2, 4, 5, 7, 8, 9 and 10), physicochemical filtration and adsorption systems (solution 6, for soluble and particulate matters), bioretention and biodegradation processes (solutions 4, 7, 9 and 10), underground separation units based on centripetal or gravitational force (solutions 3 and 5, for particulates), and (bio)flocculant-assisted bioretention and settling tank (solution 2; partially buried, for soluble and particulate matters). Simple process units can be implemented directly in stormwater sewers or manholes; for instance, vortex separators (solution 3) to remove

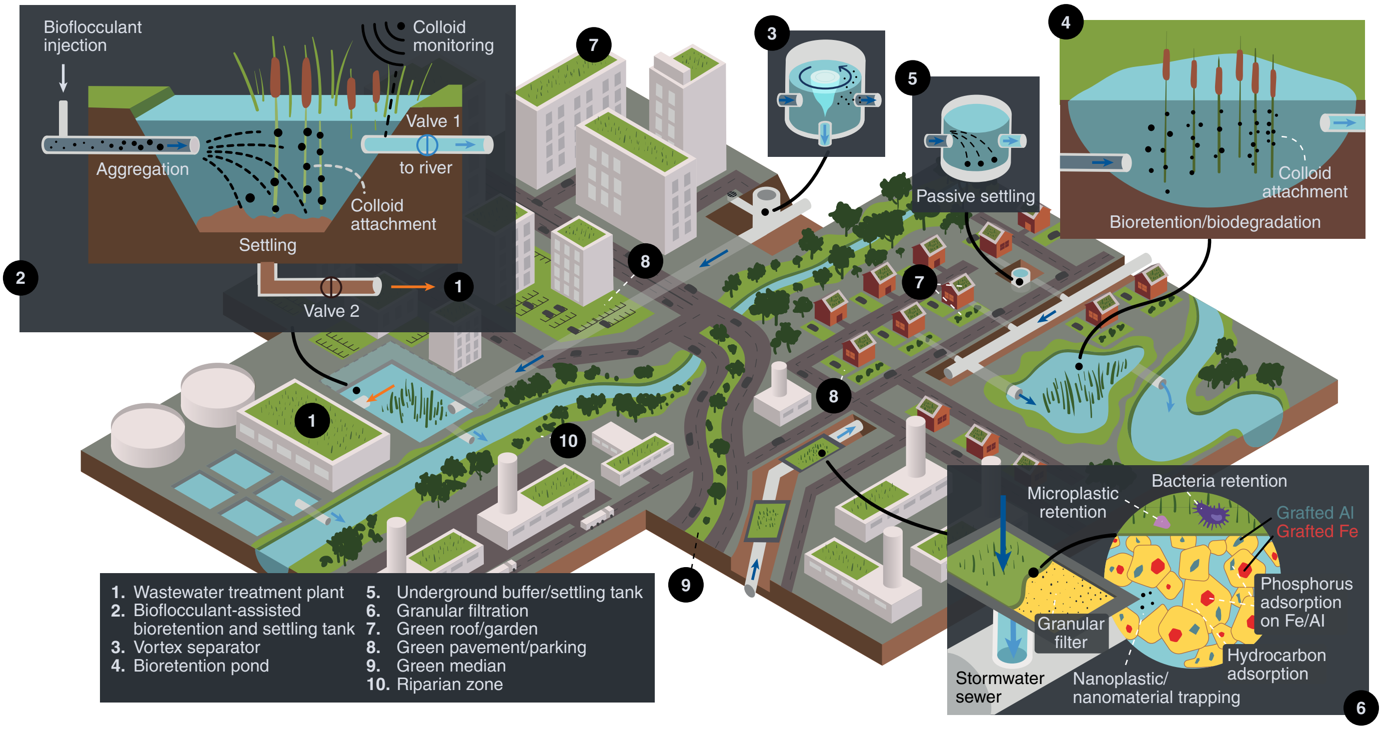

Fig. 2 | Solutions to treat runoff. Each number represents a different solution for runoff treatment, as shown in the corresponding key. In solution 2, contaminant aggregation or settling is improved with (bio)flocculants. Valve 2 is open to send settled sludge to 1 and clean water is sent back to the river. Valve 1 is open when turbidity is acceptable, or closed for longer settling. In solutions 3 and 5, centripetal and gravitational forces, respectively, separate large/dense solids from water. In solution 4, no chemical is added, colloids are removed via passive settling and bioretention. Longer residence times enable biofilm formation and biodegradation. In solution 6, recycled crushed glass grafted with metals improves colloid retention and adsorption of soluble contaminants via electrostatic interactions. In solutions 7–10, colloids and soluble contaminants are removed and the processes also act as hydraulic buffers. Arrows in dark and light blue indicate raw and treated waters, respectively. Credit: Audrey Desaulniers (Orceine).

denser particles from water, screens to trap larger debris (>10 mm), modular biofilters to remove nutrients, heavy metals and oils, and porous granular filters to trap smaller particles (<1 mm; solution 6). On a domestic scale, green roofs (solution 7, which can lead to considerable runoff reduction with only 10% of buildings having green roofs)[14], infiltration areas (for example, grass and gardens, mulches and sand-capped lawns rather than concrete pavement; solutions 7 and 8) and small (underground) reservoirs (solution 5) — all acting as surge 'tanks' or a hydraulic buffer — could also be considered to reduce the load on larger municipal infrastructure. All of these solutions could be designed with a bypass when the system is at capacity, which is expected to occur during intense rainfall events and to be exacerbated due to climate change. Moreover, to reduce cost and facilitate integration of such solutions in dense cities, some systems could be designed to deal with the runoff 'first flush', as the initial rainfall usually releases higher contaminant loads[11]. Ideally, the proposed processes must be designed to require minimal maintenance between rainfall events.

Besides the positive impact on water quality and helping to preserve biodiversity and mitigate urban heat island effects, the amount of green space in dense urban areas has been correlated with human health and socioeconomic benefits[15]. As successfully reported in some cities (for example, Philadelphia, Singapore and Hong Kong), green (treatment) infrastructure could reduce runoff flows and floods, and recharge and maintain the quality of aquifer and groundwater to secure water supply in some developing and/or arid countries[16,17]. Green treatment infrastructure in the United States currently represents <10% (US$4.2 billion) of the total capital investments used (US$48.0 billion) to address combined sewer overflows and meet water-quality objectives of the Clean Water Act[18]. Yet, several cities report that green infrastructure itself is more cost-effective than conventional 'grey infrastructure' sewer systems (for example, Philadelphia and Milwaukee)[5], in addition to reducing the load directed to wastewater treatment plants (that is, smaller sewer systems and plants are required). Moreover, with climate change and rapid urbanization, increasing green space in cities dedicated to water infiltration would reduce the risk of flooding — and its associated economic burden — caused by the growth of impervious surfaces in dense urban areas[19]. Existing green infrastructures are currently geolocalized and designed to manage floods and water accumulation. If cities are aiming for more versatile green infrastructure, the design should consider requirements for both water storage and treatment. Besides precipitation rates and intensities, the climate would also impact the design. For example, lower temperatures are known to impact adsorption kinetics in porous granular filters and increase water viscosity, which also impacts particle separation via settling. Hence, the required contact time in cold water during filtration and settling could also govern the size of the system. Moreover, the type of technology implemented (for example, granular filter versus adsorbent) will be largely influenced by local contamination patterns and water characteristics. For example, runoff with high concentrations of suspended solids (such as sand and tyre-wear particles) may require different technologies than runoffs with high levels of soluble phosphorus.

Cities have limited resources available for stormwater management. Hence, to maximize the cost-effectiveness of existing and future green infrastructures, and to reduce the risk of acute toxicity in natural waters, the proposed solutions could be coupled with more advanced process control or with data-driven machine-learning techniques[20]. Rainfall intensity–duration–frequency curves, storm water models, weather forecasts, sudden and planned events (for example, hydrocarbon spills and salts applied in winter), novel qualitative and quantitative tools, and river flows could all be included in the data stream. For example, by using such predictive analytics, the retention tanks proposed in Fig. 2 (solutions 2 and 4) could be deliberately purged to prioritize expected incoming acute contaminations; for instance, combined sewer overflows and perfluoroalkyl-substances-based flame retardants released during fire controls.

As few policies constrain the design of solutions, cities should benefit from a certain flexibility and be able to implement locally adapted, realistic, sustainable and low-cost processes. Despite the challenges to the implementation of new processes for runoff, we believe that such holistic solutions should be considered globally by cities when opportunities for infrastructure changes arise. This could mitigate and prevent the influx of contaminated runoff into aquatic ecosystems and protect animals, people and resources that are imperative to our global communities. ❐

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