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Hazards, Infrastructure Networks and Unspecific Resilience

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Abstract: The aim of this paper is to provide a framework to improve urban resilience independently of the nature of the disturbances. Recent disasters had a significant impact on critical infrastructures providing essential urban services such as energy, transportation, telecommunication, water and food supply or health care. Indeed, several natural and human-made hazards may lead to disruptions, and most critical infrastructures are networked and highly interdependent. Henceforth, resilience building remain focused on specific hazards or on improving the resilience, separately, of single infrastructures. In order to enhance urban resilience, this paper is based on learnings from three case studies that are the 2001 WTC terrorist attack, hurricanes Irma and Maria in 2017 and the 2016 Seine river flood in Paris. These events highlight disruptions to urban services, but also some resilience options. In light of both the literature and our case studies, a framework of unspecific resilience is provided for improving some resilience principles, namely omnivory, redundancy, buffering, high flux, homeostasis and flatness within electric energy, water and food supply and transportation networks. Rebuilding resilience within this framework is further discussed with respect to all kinds of disruptive events.

Keywords: critical infrastructures; hazards; urban services; disruptions; unspecific resilience

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1. Introduction

During recent disasters, most disruptions have resulted from interactions among hazards and critical infrastructures (CIs). The latter are vulnerable to natural hazards, such as hurricanes, floods, heatwaves and earthquakes, but also to human failures or terrorist attacks. Along with other major events, recent disasters such as hurricanes Sandy in 2012 and Irma and Maria in 2017, the Seine river flood in Paris in 2016, the Indian blackout in 2012, the heatwave in Europe in 2003 and the World Trade Center (WTC) terrorist attack in 2001, as well as the 2011 Japan tsunami, all share a common feature: massive disruptions in urbans services. In addition of being extremely vulnerable [1], CIs became tightly networked [2]. Their increased interdependencies make them vulnerable to cascading failures [3].

Nowadays, our societies are dependent on CIs producing or providing essential urban services such as power energy, telecommunication, water and food supply, transportation and health services. An infrastructure is basically defined as a network of interdependent man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services. CIs include, but are not limited to, electricity, oil delivery, transportation, telecommunication, water supply and wastewater treatment, as well as, financial systems, building services, food supply and health care [4]. A large amount of research has examined CIs and their interdependencies [3,5]. Indeed, many infrastructures depend on energy (electricity and fuels), while energy networks depend on telecommunications and water supply. Telecommunication networks require electrical energy, while electric power networks are managed by various telecommunication services [6]. Water collection, treatment and supply networks require energy, while most energy generation processes require water [4]. Similarly, food supply and health care depend on transportation services (of people and goods), which in turn depend on power energy [7]. In order to prevent disruptions of urban services, it seems difficult to build resilience separately from hazards or infrastructure networks.

In parallel, there is a growing set of studies on cities and resilience. Resilience refers to continue functioning or to persistence in adversity [8] and includes "the capacity to cope with unanticipated dangers" [9]. Resilience is widely used in a diverse body of literature on cities, yet there is no consensus about how to define and measure it [10]. A 'climate resilient' or 'climate proof' city, for instance, are two phrases often used to qualify a resilient city. Extreme climate events are regarded as major shocks or stressors that may affect cities and urban networks [10]. What makes the relationship between resilient cities and climate change so close is that cities are major contributors to climate change, while being particularly vulnerable to its impacts in terms of increased frequency and intensity of hurricanes, floods, heatwaves or droughts. Some studies have also attempted to link resilience to sustainability and address urban resilience as a way of future-proofing [11]. Assessing resilience therefore becomes a crucial issue given the range of perspectives offered by the use of the term resilience across diverse contexts and domains in urban areas. For our purpose, urban areas concentrate people and infrastructures and have to cope with a wider range of shocks and stresses. The notion of resilience is closely related to how well CIs continue to function. Thus, the aim of urban resilience is to maintain urban services [12,13]. Globally, resilience was primarily linked to relevant hazards [14] before a shift towards CIs such as power energy [15], water supply and treatment [16] or transportation [17,18]. Nevertheless, hazards could be unforeseen, and disruptions became unanticipated because of CI interdependencies. Rather than to build resilience on specific considerations, urban resilience may also be improved regardless of the nature of the disturbances.

In literature, a growing number of studies offer insights on how resilience may be improved. Accordingly, resilient systems are characterized by their omnivory, redundancy, buffering, high flux of resources, homeostasis and flatness [9,19]. Investigating how a territory responds in adversity, those particular characteristics were applied as resilience principles [20,21] for urban policies dealing with floods [22,23], pollution [24] or to enhance a given infrastructure's resilience [12,17,25]. Those resilience principles help to build (or to evaluate) the resilience [26]. Learning from recent worldwide events, some urban policies build on some of these principles already (Table 1). For our purpose, a more consistent application of these principles over all infrastructure networks may then improve urban resilience.

Table 1. Theoretical resilience principles and illustrative examples from current practices (Adapted from Watt and Craig, 1986 [19]; Wildavsky, 1988 [9]; Barnett, 2001 [26]).

Omnivory	Diversification of resources and their means of delivery (e.g., energy mix options, teleprocessing)
Redundancy	Interchangeability within the system functional components. If a component fails, others can take over (e.g., overhead and underground lines, secondary roads, rails and tunnels)
Buffering	Capacity in excess of the system needs (e.g., emergency generators and fuel, on-site detention tanks, local food hubs)
High flux	The faster the movement of resources through a system, the more resources will be available to cope with perturbations (e.g., mobile generators, cell towers and water distribution lines)
Homeostasis	Stabilizing feedbacks between the system components (e.g., preventive and controlled shutdowns)
Flatness	Top-heavy systems are less resilient and overly hierarchical systems are less able to deal appropriately (and rapidly) with unforeseen events (e.g., off-grid communities, inter-operators' exercises/trainings)

The remainder of this paper is organized as follows. In Section 2, three case studies, namely the 2001 WTC terrorist attack, hurricanes Irma and Maria in 2017 and the 2016 Seine river flood in Paris, are presented in order to highlight disruptions to urban services and to raise some resilience options. In Section 3, we provide a resilience assessment tool to highlight the limits of current resilience building oriented towards specific hazards or on a single CI. This section is based on learning from our case studies and other worldwide events. In Section 4, we explore unspecific resilience built on the above resilience principles. In order to maintain the continuity of urban services, each of the resilience principles is enhanced within electric energy, water and food supply and transportation networks. In light of both the literature and our case studies, an overall discussion on specific and unspecific resilience is outlined in Section 5. This paper concludes with suggestions for future works.

2. Selection of Case Studies

Recent disasters, whether natural or man-made, have led to considerable disruptions of urban services. For our purpose, we selected three case studies: The 2001 World Trade Center (WTC) terrorist attack, Hurricanes Irma and Maria in 2017 and the 2016 Seine river flood in Paris. Beyond discussing the diversity of the situations and events involved, some resilience options are also raised from those events. Data collected here are mainly from official reports, information notes or bulletins, as well as scientific papers and feedback from these disastrous events.

2.1. The 2001 WTC Terrorist Attack

The 2001 World Trade Center (WTC) attack resulted in considerable loss of life as well as massive disruptions to infrastructures in New York City. The collapse of the Twin Towers removed major transportation nodes in the basement, wireless telecommunication nodes on the roof [6] and disrupt electrical power in lower Manhattan [27]. There were more than 1500 antennas on the top of the WTC and more fiber optic cables under the streets of Manhattan than in all of Africa [6]. Financial services were severely disrupted and the water distribution system, depending upon electricity for pumping, was disabled [28]. Simultaneous disruptions of transportation and telecommunication networks resulted, as the tunnels into Manhattan provide both transportation and telecommunication conduits [29]. Floods from the damaged water pipes invaded the tunnels and the metro tracks and damaged the underground electric cables [5]. Due to interdependencies, some disruptions, such as for banking and financial systems, were longer than those of transport and electricity services [30].

This disastrous event also points to some resilient responses. Electric power was restored by rerouting power from other areas with temporary cables, lines, backup facilities and using mobile equipment. Batteries and generators were used as backup power, though their fuel supply was hampered by transport constraints in lower Manhattan [6]. Mobile generators and cell towers were moved to provide temporary wireless communications. Recovery was hastened by local availability of mobile generators from a vendor who routinely supplies them [31]. In addition, spare power from other locations and overland distribution lines connected the impacted areas to alternative sources of energy [32]. For transportation, the New York City transit system anticipated service outages, which proved to be a key factor as they were able to reroute subway trains around or away from the damaged locations [5].

2.2. Hurricanes Irma and Maria in 2017

Within a two-week period, hurricanes Irma and Maria slammed the United State Virgin Islands (USVI) and Puerto Rico in September 2017. The resulting extreme winds, flooding and storm surge led to power and communication outages, transport disruptions and fuel and food shortages.

In Puerto Rico, the two hurricanes almost completely damaged the power grid and the island's communications infrastructures. Overall, 75% of the power lines were aerial and power grid lacked redundancy [33]. Nearly 30,000 miles of distribution lines were between the power plants, located in the south of the island, and the main population, concentrated in the north [15]. Power outages interrupted fuel shipments from the Atlantic and Caribbean basins and sustained communication outages disabled electronic payments along with cash from automated teller machines to buy food. In the aftermath of hurricanes, major food shortages were observed in Puerto Rico as the island heavily dependent on external supplies. Although the port was later clogged with relief supplies and goods, the blocked roads prevented the delivery of food across the island [34].

In the USVI, many disruptions were similar to those in Puerto Rico. Failures of transmission and distribution power lines and transformer infrastructures generated electric outages [35]. About 90% of the overhead power lines were damaged, but not the underground part of the network [33,35]. It is worth noting that most water services did not fail even with some damages to water production facilities and pumping stations. Most significant disruptions to the water system came from the lack of electric power [35]. Raw materials, spare parts and 800 linemen were brought in from off-island to restore the power grid [36]. Unlike Puerto Rico, almost all households in the USVI are equipped with cisterns to collect rainwater for household use [33].

2.3. The 2016 Seine River Flood in Paris

Paris, and its suburbs, was flooded in May–June 2016. The Seine water level rose about six meters, just two meters below the level of the major 100-year flood of 1910. Serious disruptions in transport, electric energy and water systems were identified in and beyond the flooded areas. Many roads, tunnels and highways, such as the main highways A10 and A86, remained cut off, and the regional express train (RER C), which carries nearly 550,000 passengers daily, was closed from 3 June to 10 June 2016 [37]. According to the General Council for the Environment and Sustainable Development (CGEDD) and the General Inspectorate of Public Administration (IGA), the interruption of waterways on the Seine basin for one week hampered the refineries' fuel storage and distribution activities [38]. Preventive shutdowns were carried out in some electrical substations as well as in some waste treatment facilities and water treatment plants [39]. The exposure of the electric network to flooding is significant, as most of the power and communication lines are underground. The shutdown of 22 wastewater treatment plants for about 6 days impacted the drinking water networks [40], and the power outages affected more than 16,000 customers and hampered public transportation signal systems, public lighting, urban heating and water services beyond the flooded areas [37,38]. Other services such as waste collection were also temporarily interrupted in some places because of flooded roads, lack of fuel or lack of electrical energy powering the waste treatment plants. To ensure the continuity of underground transportation, groundwater pumping is routinely achieved by the RATP (state-owned public transport operator) [41] and in case of flooding, CIs are increasingly run by teleprocessing of remote-controlled equipment [42].

3. Resilience-Building Assessment Tool

Resilience assessment involves a process of identifying how resilience is created, maintained or broken down [43]. In this section, a qualitative tool is used to assess current resilience building. Mapping and modeling may enable policy makers to address hazards and prevent CI failures [44]. Learning mainly from our case studies, this tool connects five components to better understand the scope of management interventions with respect to urban resilience (see Figure 1, Table 2). The key components identified are "hazards", "infrastructures" and "responses" to capture current resilience approaches that build on relevant hazards and/or a single critical infrastructure. The additional components of "pathways" and "disruptions" respectively refer to secondary sources of disruptions that may result from the focus on "hazards", and to any dysfunctions of urbans services due to CI interdependencies.

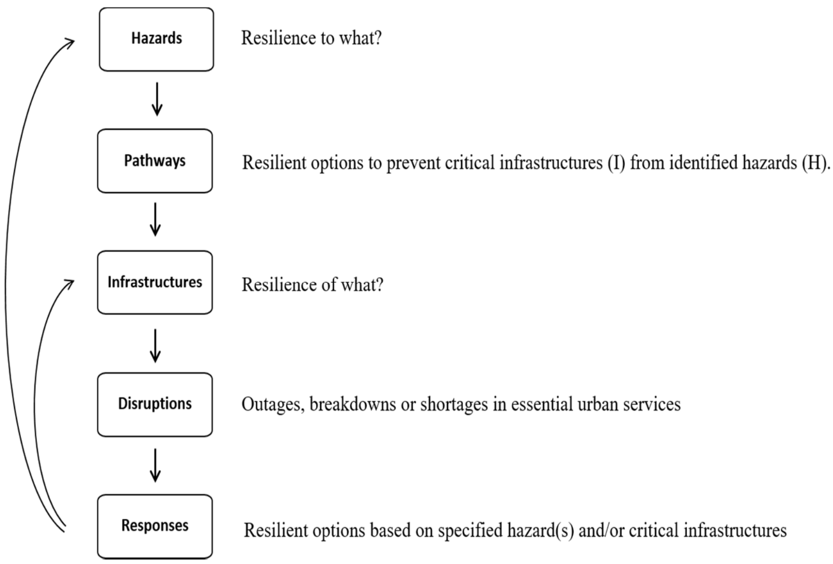

Figure 1. A scheme of current resilience-building assessment tool.

Table 2. Components of the qualitative tool HPID-R assessing current resilience building.

Hazards (H)	Resilience to what? Most resilience approaches target the man-made or natural hazard to maintain the continuity of urban services. However, some hazards could be unforeseen, and disasters could result from multi-hazard interactions.
Pathways (P)	In order to prevent CIs (I) from the identified hazards (H), some of the resilient options became a secondary source of disruption. For instance, some of the selected technological responses against flood (e.g., dyke's or water dam's failures, sewage system overflowing) could generate disruptions.
Infrastructures (I)	Resilience of what? Recent approaches are oriented towards fostering the resilience of CIs such as energy power, transport, telecommunication, water or food supply.
Disruptions (D)	All potential outages, breakdowns or shortages in essential urban services. Due to interdependencies, any failure may spread disruptions across networked CIs.
Responses (R)	What is done to improve resilience? Resilience is mostly built on specific hazards and/or improving the resilience of a single CI.

In light of our case studies along with other recent events, Figures 2 and 3 (see below) provide a graphic representation of disruptions to urban services. Figure 3 offers a wider view for specific hazards or on single CI approaches in building resilience.

Figure 2 displays a basic illustration of urban services disruptions due to heavy rainfall and strong winds damaging the CI (e.g., electric grids, water stations, transport facilities). First, some of the selected responses became a secondary source of disruption (e.g., dyke's or water dam's failures, sewage system or basin storage overflowing). In the Paris area, flooding derived from the drainage system saturation due to combined sewage networks and the rising of the groundwater table, but also from ventilation ducts causing serious damage in the underground transportations facilities as well as water pollution [42]. In addition, the continuity of the underground transportation operations may affect sewer networks. Routinely, a continuous water pumping is required to protect underground transport infrastructures from water [41]. As the water pumped is discharged into the sewer network, the latter overflows under heavy strain [41] and induces flooding of roads and tunnels. It is worth noting that sanitation is widely dependent on electric power, that emergency reliefs are dependent on transportation systems and any telecommunication or electric energy breakdowns may inhibit the teleprocessing solutions. Preventive shutdowns in water or electric stations may thus interrupt all interdependent infrastructures.

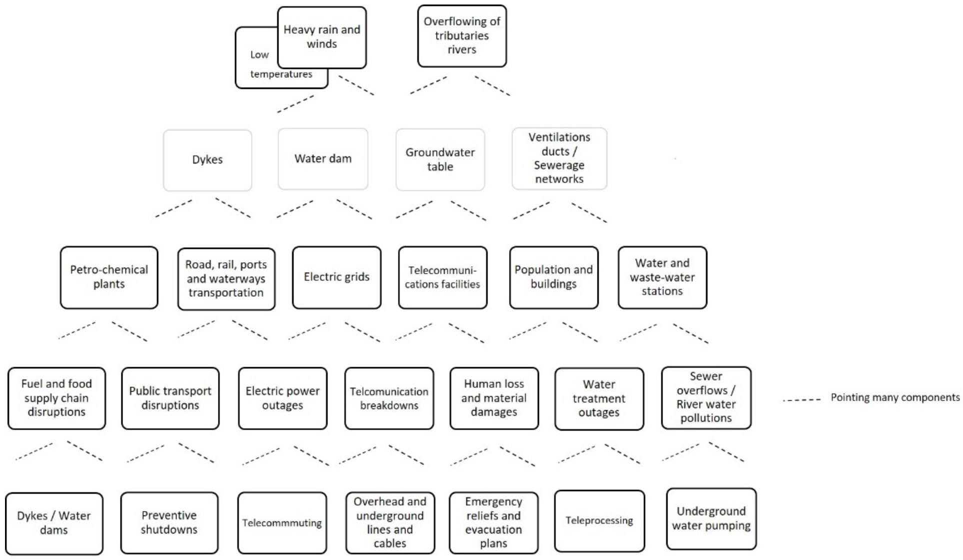

Figure 2. A basic illustration of disruptions to urban services in case of flooding (Author).

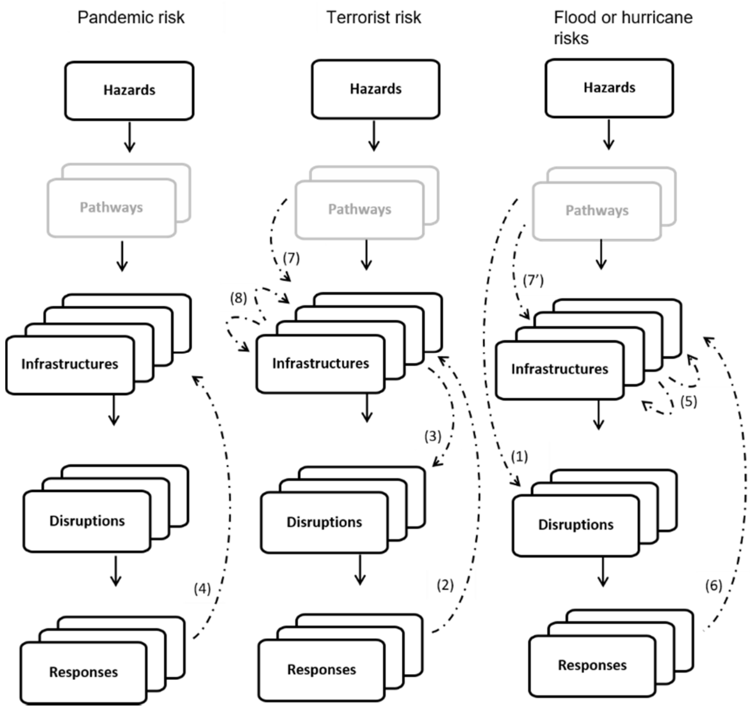

Figure 3. Disruptions to urban services in current resilience building (Author).

On the basis of past disasters, Figure 3 provides a wider perspective on some of the resilient responses to disruptive events resulting from floods or hurricanes, terrorist attacks or pandemics.

Consider the following in light of the case studies introduced previously and other disruptive events:

(1) Dyke's or dam's failures (in case of floods or hurricanes) trigger disruptions in power plants and/or petro-chemical manufactures.

(2) In order to deal with a terrorist attack, government restrictions of shared information on electric energy impacted other CIs, especially hospitals depending upon electric power data for their locations and emergency plans [45].
(3) For security concerns, the U.S. government closed its borders and all air transportation was halted for about three to four days [46]. The shutdown of all flights had immediate impacts on many supply lines.
(4) To deal with the COVID-19 pandemic, lockdown policies generated transport outages. Moreover, telecommuting solutions have generated an unprecedented number of cyber-attacks targeting computer systems of many urban networks such as wastewater treatment plants [47]. It is worth noting that telecommuting depends on telecommunication and electric energy and that hazards may co-occur: during the lockdown period, a devastating earthquake, 5.5 on Richter scale, caused significant damages to Cis, such as water, gas and electricity, in Croatia's capital Zagreb (Press).
(5) During Irma and Maria hurricanes, disruptions in telecommunication and transportation hampered the food supply. After the 2001 WTC attacks, the recovery of telecommunications, banking and financial systems were hampered by the power and transportation system outages [30]. Similarly, electric or telecommunication outages may hamper pre-established responses (e.g., teleprocessing).
(6) Preventive or controlled shutdowns in water stations, oil refineries or nuclear plants impact other urban services.
(7) Digital transformation of energy systems improves its resilience at the expense of greater exposure to cyber-attacks and widespread disruptions over several interrelated sectors [48,49]. Similar interactions exist between transportation and sewer networks. In view of the rising water tables, the resilience of the underground transportation networks may negatively affect the sewer networks functioning in case of a major flood.
(8) In case of impact, co-located electric cables, water pipes and telecommunication lines are simultaneously disrupted due to physical proximity.

First, resilience building focused on relevant hazards allow for a main consideration to be on known events, rather unknown ones. While some disruptions could be experienced and predictable, others could be unforeseen. Secondly, urban resilience policies shift recently towards CI to improve resilience, yet any single optimizations should take into account their interdependencies [7].

In Figures 2 and 3, many of the "responses" capture some options of omnivory, redundancy, buffering or homeostasis. A more consistent application of the set of resilience principles to all interdependent CIs may help to improve urban resilience.

4. Unspecific Resilience Proposal

In this section we explore unspecific resilience by improving some characteristics of resilient systems within a set of essential urban services. There is much value that can be learned from resilience-oriented hazards or from single infrastructure optimizations seeking resilience. However, a consistent application of some resilience principles, namely omnivory, redundancy, buffering, high flux, homeostasis and flatness, may help to build more systemic resilience. Regardless of any specific disturbances, we suggest improving each of these resilience principles for electric energy, water and food supply and transportation networks. A synthesis of some resilience options is presented in Table 3 (see below):

- Omnivory involves a diversification of approaches/ways to reach one need. Resilience is improved by diversifying resource requirements and their means of delivery [26]. The omnivory principle may help to free infrastructures from resource dependency, e.g., exclusive reliance on fuel for power energy or on narrow road/tunnel to ensure urban mobility. In light of feedback from our case studies, most of urban services require electric power, while power networks are usually the last to recover in case of impacts. Unlike Puerto Rico, some off-grid wind and solar energy systems survived the hurricanes Irma and Maria in the USVI [50]. Less electricity-dependent use in household activities, buildings' daylight technics [51], diverse energy user needs per area and energy mix options (including solar panels, wind power, fuel cell systems, etc.) help to ensure continued power services. Technics like bioretention basins, cisterns for rainwater harvesting and several water supplies, such as storm water and natural reservoirs, may improve water supply services. For transportation, some of the omnivory options could be telecommuting, teleprocessing, carpooling, soft modes of transport for daily travels (pedestrians, cyclists, etc.) and more energy-efficient cars using diverse power generation (see more options in Table 3).

- Redundancy is essential for urban services to provide interchangeability within its functional components. Redundancy provides "insurance" by allowing some elements to compensate for the loss or failure of others [52]. Redundant components, not identical but playing a same function, make greater options to persist in adversity. Residents and businesses in buildings owning multiple providers for telecommunication were more likely to maintain communication during and after storm Sandy's outages [24]. Some examples of redundancy from our case studies are the combined overhead and underground lines for power transmission, the "separate eight networks for the electric power distribution system in Manhattan" [32] and the multiple track systems for transportation in New York City. Redundancy may be enhanced by components (secondary roads, rails, tunnels, power lines, pipes, etc.), but also by subsystems (substations for energy power and for water and wastewater treatment, etc.). For instance, transportation redundancy may be enhanced by redundant transport facilities (vehicles, trucks, barges, ships, freight cars and airplanes) and redundant paths through various transport modes (land, rail, river/sea and air).

In Table 3, it is worth noting that passive redundant components exist as well as active ones. Passive redundant components act as spare units held in reserve (e.g., emergency water storage in industrial plants or food reserve for households) unused except in case of disruptions, while active redundant components (e.g., secondary roads or energy substations) are usually used and also allow for switching from one to another if needed. Redundancy is closely related to omnivory, but the latter has the key goal to prevent fate sharing. Redundancy consists of variety (how many different components there are?) while omnivory consists of disparity (how different are the ways/means to reach a given need?). Today's urban services use more redundant components, e.g., overhead and underground lines, secondary pipes or many power/water substations, than diverse ways/means for power energy generation or water supply. Thus, telecommuting or teleprocessing as omnivory options in transportation networks usually remained impaired by electric outages because of the lack of omnivory in power energy.

- Buffering should allow urban services to absorb the disturbances up to certain thresholds. It refers to the "moderation (lessening) of impacts from disturbance" [53]. This principle advocates high capacities to resist ongoing disruptions, as some of the resilience definitions refer to robustness of the system's physical components to measure buffering capacity. On one side, buffering is improved by hardening components like cables, lines, pipes, tanks and pumps, using resistant materials for roads, buildings and transport facilities to absorb physical impacts. On the other side, buffering also means that essential needs are oversupplied so that critical thresholds are less likely to be crossed. Then, it may also be improved through rainwater harvesting and the retrieval of storm-water treatment [7], rainwater tanks and greywater use, on-site detention tanks and cisterns, kitchen gardens in common, food and energy storage solutions, etc. Large multipurpose reservoirs such as dams and sewer networks also play a buffering role for water and wastewater networks. However, buffering also suggests a need to ramp up stocks of emergency supplies in households, retail stores and manufacturing, but also in necessary resources for operators and hospitals. For instance, hospitals in the United Kingdom are required to have 11 days' diesel fuel supply to run generators [54]. In the USVI, backup power by small rooftop customer-installed solar panel allowed their infrastructure to resist the power outages [55]. Henceforth, strengthening only buffering may promote self-reliance if it is not balanced by high flux.

- High flux is achieved by a rapid mobilization of resources in urban areas. A rapid flow of urban services is well achieved nowadays by infrastructure networks providing urban services. An example from our case study is the mobile generators, cell towers and flexible distribution lines providing temporary water, energy and communication services during the 2001 WTC attack. However, in parallel to increased urbanization, many infrastructure components are co-located to promote rapid transfers of power energy, transport of people and goods and water and food supply. Co-location enables a shift from one component to another, and economies to be in construction and maintenance, but also widespread disruptions due to spatial interdependencies [5]. Moreover, most of resources now flow from centralized plants, large infrastructures and long transportation distances [56]. Linear infrastructures carrying flux (such as a highway or a commuter rail track) run parallel to power lines, telecommunication cables, gas pipelines and water pipes [57]. The one-way direction of water networks offers fewer options in case of any failures for the Île-de-France [40]. In light of above, Table 3 presents some options for high flux. Note that overconnected systems can lead to undesirable outcomes [58], and higher interdependencies spread disruptions. Elaborating on this, high flux and buffering principles should balance one another.
- The homeostasis principle suggests several feedback loops between the system components to counteract disturbances, to signal changes and to maintain stability [22,26]. From our case studies, preventive or controlled shutdowns of certain infrastructure components reflect this principle. During the 2016 Seine river flood in Paris, some water stations were intentionally shut down (or bypassed) [16] thanks to other stations (of larger treatment capacity) for whom the water discharges were redirected. A similar mechanism is the controlled shutdown (i.e., de-energizing) of three of the eight separate power networks before the collapse of the WTC building 7 to prevent a catastrophic shutdown. Compensatory flows from other locations were then required to supply the approximately 13,000 affected users [32]. Automatic mechanisms such as opening or closing of valves/pipes or roads/tunnels may help to counteract disturbances and bring stability. However, homeostasis also has a long-term scope. It may help to proactively prevent any mismatch between demand and supply trends, since disruptions may result from a largely oversized (or undersized) infrastructure networks. Indeed, recurrent breakdowns in the water supply have resulted from a largely oversized technical network on the one hand and, on the other, a demographic decline and a decrease in water consumption in Eastern Germany [59]. Likewise, power outages could also result from the larger generators compared to the utility needs in the USVI [36]. India experienced two blackouts in 2012 due to an unexpected increase of electricity demand (from agriculture) that disrupted the relatively undersized northern grid according to the International Energy Agency (IEA). Compensatory flows from eastern and western grids ended up, unfortunately, with a massive blackout [60]. A dynamic scaling is thus necessary among the supply side (i.e., infrastructure networks) and demand side (i.e., end users).

A desirable stable state could be sustained with regard to some indicators of urbanization and efficiencies of energy, water and transportation networks. Transportation planning (e.g., building roads, highways or rails) influences urban growth, trade, industrial and residence settlements as well as growth patterns that may require more transportation facilities, energy and water services. Some indicators (e.g., commuting time, gas emissions, transport congestion, density, electrical cable length, road surfaces, etc.) may help to signal (ir)regular changes and guide relocation strategies for load centers, heavily populated areas and industrial or agriculture sectors (Figure 4).

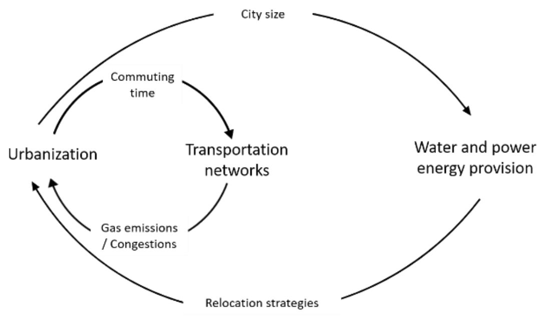

Figure 4. Feedback loops to match urbanization and urban services of transportation, water and energy (Author).

- Flatness refers to governance arrangements and hierarchical pyramid levels in decision-making. The collapse of the De la Concorde overpass in 2006, near Montreal, is a narrow example of overly hierarchical systems. Rigid chains of command prevented an inspector from the Ministry of Transport to close the overpass (and highway 19) without decision-making from a higher level in the hierarchy [61]. For our purposes, flatness refers first to coordinated actions, as several sector-specific actors intervene to maintain urban services. For example, the RATP (state-owned public transport operator) as well as Orange (France Télécom operator) discharged pumped water into the sewer networks and into the road network while there were no up-to-date exchanges with the SAP (Paris sewer managers) on the volumes and points of discharge and on the load capacities of the sewer system [41]. Interdependencies of urban services thus implies some mechanism of collaboration within a given sector, between sector-specific (i.e., CI operators/owners) and cross-sectoral structures (i.e., public-public entities, public-private entities). During the 2001 WTC attacks, cross-sector collaboration was critiqued for being less frequent, and systematic collaborations were noticed even between some public agencies belonging to different jurisdictions [62]. Pre-arranged coordination across levels and stakeholders is necessary for urban resilience: for instance, a mismatch between electric power and gas firms induced additional fires as early restoration of power was realized with leaking gas in some areas during the Kobe earthquake in 1995 [63]. In addition, flatness suggests intertwining of local and higher levels of governance through centralized and decentralized stakeholders and resources. Indeed, local expertise (e.g., linemen) and necessary materials to restore the power grid were brought in from off-island in the USVI. Learning from our case studies, local and decentralized actions may provide a kind of isolation from the effects of damages [6] as most urban services are provided from distant and globally-oriented infrastructures. In the USVI for instance, off-grid opportunities are pushed back and less promoted than the existing energy, and transport, housing, agri-food or water systems are largely stabilized by lock-in mechanisms [50].
  In light of Table 3, the resilience principles often overlap [52] and are interrelated, as are urban services. Build on these principles, unspecific resilience mainly addresses how to maintain essential urban services by dealing with unavoidable hazards, unforeseen events and failures.

Table 3. A portfolio of generic options based on resilience principles.

	Omnivory	Redundancy	Buffering	High Flux	Homeostasis	Flatness
Electric energy	- Diversity of energy sources including renewable technologies such as solar photovoltaic, wind, geothermal, hydro or bioenergy. - Analog and digital devices for control systems - Energy mix options - Less electricity-dependent uses - Buildings daylight technics	- Separate substations and networks for energy generation and distribution - Overhead and underground cables/lines - Subsidiaries/subcontractors in energy providers - Various locations for energy substations - Conventional electrical grids and individual solar energy kit	- Back up energy and battery storage - Energy-efficient buildings - Combination of larger and smaller number of end-users per area - Resistant building materials and components - Hybrid microgrids - Small-scale solar generation on rooftops	- Mobile generators - Less distance between energy sources and end-users - Matched to demand systems to adapt the quantity of energy needed to where and when its needed - Interconnections by cables, lines, pipes, etc. - Backup generators pre-wired or in place	- Preventive and controllable shutdowns - Readily adjusted systems - Relocation of load center strategies - Dynamic scaling of demand - Economic incentive to counterbalance excess or deficits in energy services	- Communities of off-grids - Local resources to build-own, operate and repair - Decentralized renewable technologies - Strong public/ private partnerships - Shared information among CI planners/operators/owners - Local materials, expertise, operators/owners and developers - Small-scale programs
Food and water supply	- Less water-dependent activities. - Technics like bioretention basins, rain gardens, cisterns for rainwater harvesting, etc. - Several water supply as storm water, natural reservoirs, desalinated seawater and reclaimed water - Hybrid green and grey infrastructures	- Water substations and secondary reservoirs/pipes - Water storage in elevated, ground supported or underground tanks - Many food suppliers/retailers - Urban farmland for local food production and processing - Pre-plans with multiple access for food suppliers	- Large multipurpose reservoirs - On-site detention tanks and cisterns - Grey infrastructures for water treatment - Local food supply chains - Food hubs using garden share, rooftop and unused back gardens - Urban permaculture - Prepared food, meals-Ready-to-Eat, bottled water, etc.	- Mobile and flexible distribution lines - Bi-directional circuits in water and wastewater systems - Cross connections of supply lines for water and wastewater - Local reclamation for wastewater plants - Local and supra-local supply chains for food provision and trade	- Dynamic monitoring between water networks, food supply and the population size - Interconnected water stations and smart grids for supply and discharges - Adjustable devices for valves/pipes controls	- Local and regional water board - Micro, meso and central reservoirs. - Decentralized circular system for water, sanitation and waste infrastructures - Less long pipelines and polycentric configurations - Retailers, small businesses and local food supply chains - municipal water supply and wastewater
Transportation	- Telecommuting and teleprocessing - Soft transport modes for daily travels (pedestrians, cyclists, etc.). - Carpooling	- Transportation infrastructures including highway/roadways, mass transit, rail, aviation, shipping and intermodal facilities - Secondary paths, roads, tunnels, bridges, ports, etc. - Hybrid energy for transport vehicles - Multiple transport companies	- Autonomous vehicles - Ride sharing services. - Robust infrastructure - Over-dimensioned roadways, tunnels, ports, etc. - Less distances and commute time	- Remote access for banking, trades, education and healthcare advices - Intra- and inter-urban transit connections - Real-time traffic monitoring	- Transport incentives related to congestion, oil price and mode of individual transport - Fixed-term renewable buildings permits - Incentives to balance sprawl	- Public-private partnerships. - Mini-grids projects. - Inter-companies and operators' exercises/trainings. - Door-to-door delivery service.

5. Discussion

The more notable the disruptive events are, the more attention is brought to the concept of resilience. Cities are facing numerous risks and resilience, as a concept and practice, embraces now many fields, sectors and disciplines in urban areas.

5.1. Resilience Is a Commonly Shared Concept Missing for a Common Shared Interpretation and Translation into Practices.

In urban areas, resilience is the goal of current urban policy to ensure essential services providing for society. In the literature, a growing variety of definitions exist for "resilience", but also various interpretations and uses for the same initial concept [64]. Learning gradually from past events, resilience approaches were oriented against hazards before shifting to optimize and perform subsystems in each of infrastructure networks. Diversity of fields, sectors and domains intertwining in urban areas naturally gave rise to diverse interventions seeking several resilience(s) for a same territory. The HPID-R conceptual tool used here might contribute to highlight the limits of purely disciplinary approaches. Cities, as complex systems, and resilience, as a systemic concept, meet in risk management. The latter has been mainly driven by disciplinary approaches ensuing single risk management. Used simultaneously but separately in many fields, the resilience concept has been interpreted diversely. Specific resilience(s) is thus a logical result of specific considerations through less systemic, analytical or single hazard approaches.

5.2. Resilience Principles Are Inter-Related, as Are Urban Services

Energy services are linked to water systems and to transportation, which in turn is linked to energy and vice versa. Equally, the resilience principles listed above are linked to each other in practice. From our case studies, homeostasis options, such as preventive shutdowns in energy or in water stations, require a certain level of high flux through mobile generators and temporary water lines to maintain the continuity of energy and water supply services. Likewise, buffering in energy services through a "small rooftop customer-installed solar panel" would require some flatness level through small-scale programs. Similarly, redundancy options, such as underground/overhead cables, secondary pipelines and roads, are no longer sufficient without some level of omnivory through diverse power sources, teleprocessing and telecommuting. In addition, it is noteworthy that these resilience principles overlap. As an example, buffering with water dams provides flood control, water storage (for household, industrial and agricultural), but also an omnivory option with relatively less hazardous energy sources. As do drainage and sewerage networks buffering for water services, which also allow for high flux through cross-connections of water and wastewater supply lines. In regard of interdependencies, each resilience principle is not sufficient on its own to improve urban resilience in view of CI interdependencies.

The suggested resilient options presented in Table 2 are only illustrative examples and it is tricky to implement them all. Some of these options are more or less suitable to be combined with others. Resilient principles may, then, offer many possible equilibriums to maintain urban services.

5.3. Unspecific or Specific Resilience(s) for Urban Areas?

Feedback from recent disasters shows that most of the affected territories have been rebuilt in some form. If any rebuilding or post-disaster recovery makes a city resilient, to what end is the concept of resilience useful? Our case studies highlight a number of disruptions to urban services, even with some resilience options related to the resilience principles. Targeting a specific hazard or improving a given CI's resilience, these options have not been applied in a systemic way: For instance, restrictions on shared information about electrical power, after the WTC terrorist attack, provide a buffer option that calls for a high degree of buffering in interdependent services such as hospitals. As well, groundwater pumping that buffers the underground transportation calls for a corresponding level of buffering in sewerage networks in case of flood in the Seine river. In this respect, our framework may offer a perspective to rethink resilience building. Major discrepancies are seen between "maintain functions" and "recover/bounce back" when exposed to changes or shocks. Systemic definitions of resilience refer to the ability to absorb shocks, reorganize and continue to develop without losing fundamental functions [20], while engineering resilience's definitions (at subdomain and subsystems levels) refer particularly to quickly "recover" from a disruptive event [64]. As framed in this paper, unspecific resilience falls within a holistic view of urban systems that aims to maintain its essential urban services, including recoveries from failures in its subsystems or subdomains. The terms "recovery" or "bounce-back" are closely related to engineering resilience and are synonymous to a focus on the equilibrium of a single system [65]. Within our framework, recovery or bouncing-back are the property of components and subsystems (e.g., a given road transportation or power grid), while the system as a whole (e.g., an urban area) must maintain the continuity of its urban services if it is to be resilient. From that point of view, urban resilience refers, in theory, to the ability to maintain uninterrupted urban services if resilience principles are improved within the interdependent CIs. Compared to specific resilience, unspecific resilience provides only a broad framework for which all specific resilience(s) could be explored more systemically. Unspecific resilience and specific ones are not at odds, as any oriented resilience (dealing with hazards or optimizing such a subdomain or subsystem) would need to converge towards a more global goal, namely urban resilience.

5.4. Re-Building Resilience Needs to Assume Unpredictable Events

Resilience principles provide a broad framework to enhance CIs' resilience against all hazards and emergencies. Prevention-based modeling is essential to produce knowledge and prevent failures. However, resilience building should also encompass responses for unexpected and extreme disturbances [20]. In urban environments, future disruptive events may be completely new and, then, unpredictable. In order to persist and continue functioning, re-building resilience on the basis of the above principles is likely to cope with less predictable and extreme events. To anticipate a wide array of disturbances, unspecific resilience paradigms shift the emphasis away from reducing the likelihood of such disruptive events to strengthen the urban services themselves.

6. Conclusions

In order to build urban resilience, this paper advocates a paradigm shift from a focus on disruptions to a focus on urban services themselves. For the resilience approaches, it underlines an improvement of some resilient characteristics within the urban services rather than mitigating the numerous, known and unknown, hazards and CI failures. In line with this, the grounded "risk culture" may gradually be replaced by the "resilience culture" to cope with uncertainty of future disturbances in urban areas.

This framework requires further development since it is only based on certain urban services. We did not deeply explore details in resilient options as each of the urban services represent a complex subsystem in its own. Examples of compliance or contradictory options among specific and unspecific resilience building have then to be assessed in urban contexts. Nevertheless, the notion of urban area remains critical. From a CIs perspective, the spatial criterion alone is no longer relevant to consider a giver urban area as a "system", since most cities are interconnected.

Besides, this proposal of resilience building may contribute to the debate of pluralistic use of the term "resilience" leading to plural interpretations and practices. We believe that resilience is a systemic concept encompassing all kinds of disturbances. A given territory could not be resilient to a given disturbance and, at same time, not being resilient to others. In light of the resilience options outlined in this paper, re-building resilience here may offer a perspective to meet resilience and sustainability in urban areas.

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