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Urban climate resilience through hybrid infrastructure☆

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Urban infrastructure will require transformative changes to adapt to changing disturbance patterns. We ask what new opportunities hybrid infrastructure—built environments coupled with landscape-scale biophysical structures and processes—offer for building different layers of resilience critical for dealing with increased variation in the frequency, magnitude and different phases of climate-related disturbances. With its more diverse components and different internal logics, hybrid infrastructure opens up alternative and additive ways of building resilience for and through critical infrastructure, by providing a wider range of functions and responses. Second, hybrid infrastructure points toward greater opportunities for ongoing (re)design at the landscape level, where structure and function can be constantly renegotiated and recombined.

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Introduction

Much of the urban infrastructure is aging, designed based on outmoded principles of carbon-based energy, risk and equity [1,2,3•], or it is yet to be built [1]. At the same time, new climate and weather-related disturbance regimes are putting critical infrastructure and human lives and well-being in peril [4]. We face a time when extreme weather events are becoming more frequent, less predictable and more severe, and cascading infrastructure failures are becoming increasingly commonplace [e.g. Refs. 5•,6–8]. For example, in 2017 the US Territory of Puerto Rico was ravaged by two major hurricanes within weeks of one another, leaving virtually the entire island without power as the aging grid could not withstand consecutive impacts. In northern Japan in September 2018, heavy precipitation coinciding with an earthquake made the effects of the earthquake much more severe due to extensive landslides, triggering a cascading infrastructure failure. These developments have laid bare the extent to which planners, engineers, and managers are confronting rapid changes in the Earth's systems that their infrastructure and governance systems are woefully inadequate to absorb [e.g. Ref. 9].

Strong traditions in infrastructure planning may hide assumptions and simplifications, and may reinforce existing 'solutions' rather than explore alternatives when the urgency of climate change calls for innovation. This paper will explore emerging insights and opportunities for hybrid infrastructure design to contribute to resilience against extreme events. We understand infrastructures as *natural or designed and managed spatial systems* that provide services to people, and that they are *interconnected* via *flows or transfers of materials, energy, organisms, people and information*. In *hybridity* we attempt to capture a quality emerging from relations, real and conceptual, between landscape-scale biophysical structures and processes inherent in ecosystems like salt marches, urban woodlands and rivers (green and blue infrastructure) and the built, human-engineered environment consisting of, among others, roads, power-grids, buildings, sewers and levees (grey infrastructure) [10,11]. More specifically, our primary focus is on the infrastructure that helps a city to *modify or respond to climate change induced biophysical variability, which often share elements from grey, blue and green*

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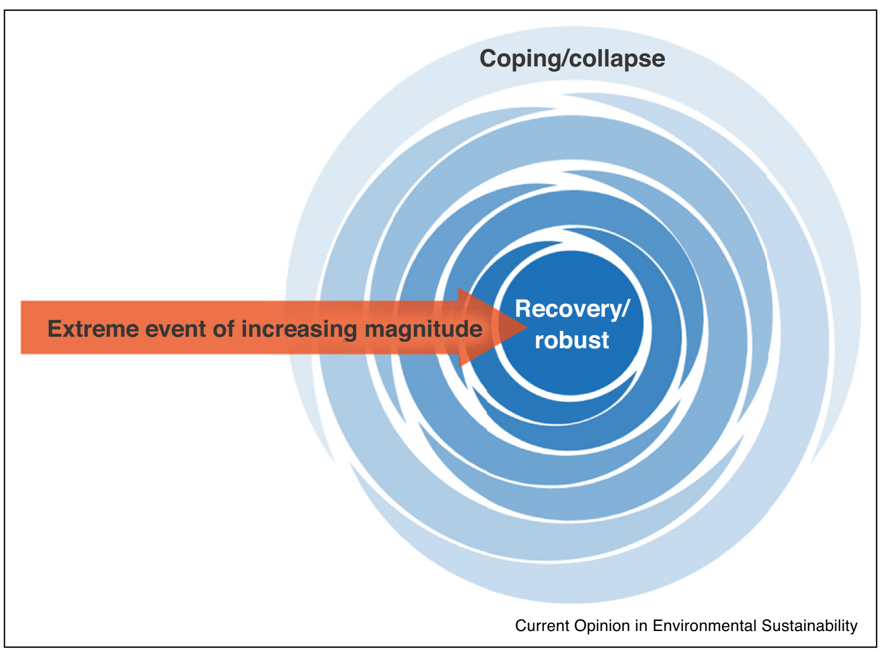
infrastructure. Basic principles for enhancing resilience in functions vital to urban systems [3•,12,13] are still tentative, especially with respect to couplings between infrastructure, biophysical processes, and the built environment [8,14,15,16••]. Also, such principles for building resilience do not necessarily translate into comprehensive, holistic strategies for infrastructure design. Drawing on recent advances in complex systems analysis, ecological resilience theory, and environmental governance, we propose a design framework with four themes: *attenuation*, *variable connectivity*, *facilitated reorganization*, and *flexible multifunctionality*. The framework is intended to help designers and scholars to identify and assess hybrid infrastructure projects offering solutions that can deal with multiple disturbances of varying magnitude, during as well as after events.

Layered resilience through hybrid infrastructure

Grey infrastructure, and its role in urban risk management and resilience is a vast and well-established field, even if the interest in resilience and through it in longer time frames and flexibility is more recent [e.g. Refs. 17,18]. There is also a growing literature on ecological engineering, green and blue infrastructure, ecosystem services and nature-based solutions exploring green contributions to urban resilience [e.g. Refs. 19•,20•]. However, the unique contributions or opportunities in combining the two are less explored [21]. The life cycles of green and grey infrastructure are distinctly different. One central difference is that societal functions of green infrastructure are characterized by regenerative processes, while grey infrastructure to uphold functions need substantial financial investment in continued engineering dealing with material decay. The knowledge and resources needed to work with them are often associated with different, commonly disconnected sectors. While these differences clearly pose a challenge, they are also a source of diversity that can be used to build layers of resilience. With the increasing need to build urban resilience not only to different climate-related disturbances but to different magnitudes and novel sequences of disturbances, hybrid infrastructures opens up new avenues for design (Figure 1) and bricolage. Our approach to hybridity focuses on interdependent functionality, capturing and highlighting a wider range of potentially reinforcing (or detrimental) connections and interactions between grey and green components.

The resilience literature describes different responses to disturbance, from resistance and coping to reorganization and transformation, and the resultant overall capacity to respond is built through the combination of structure itself, its processes of maintenance, and how function

Figure 1



Responses to disturbances of different magnitude. As disturbances increase in magnitude or frequency, measures that help the system cope may be overrun or collapsed. Multiple layers of coping mechanisms, like layers of an onion skin, with different functions and responses to disturbance make it less likely that all will collapse. Hybrid infrastructure offers more different ways of balancing robust and more dynamic features. This is important when exploring opportunities in collapse and planning for recovery and reorganisation, which provide a less explored counterpoint to attenuation and harm reduction.

Table 1

Four components of resilience through and of infrastructure. Hybrid infrastructure, with its roots in two different systems and logics, offers new ways for moving beyond robust and safe to fail systems through a focus on self-organization and broader actor involvement. The four ways hybrid infrastructure can help build resilience around critical urban functions each has its specific role and place during and after a disturbance.

	Link to resilience	Green and blue infrastructure/ ecology	Built infrastructure/engineering	Hybrid infrastructure
1. Attenuation				
Attenuating the strength and magnitude of disturbance.	Functional diversity (in terms of mitigation effects), reinforcement.	Biodiversity at levels from genes to ecosystems potentially offers a broad suite of mitigation functions against multiple disturbances but is also sensitive to disturbances. Life-history trade-offs between coping, withstanding, and quick recovery. Ecosystems are expected to collapse at times.	Responses tend to be disturbance- and threshold specific, designs intended to be robust up to the limits of the design specifications. Mutually reinforcing and complementary layers of external protection around infrastructure possible but costly.	Semi-autonomous, mutually reinforcing and complementary layers of external protection around cities and critical infrastructure. Different degrees of hybridity are possible. Low cost 'inert' layers for coping also with severe disturbances.
2. Connectivity				
Containment or rerouting flows by changing infrastructure connectivity.	Connectivity and modularity, decoupling and rerouting flows.	The risk of cascading disturbances can be reduced by heterogeneity (ecosystems, successional seres, conveyance and absorption areas etc.) and functional shifts within the infrastructure (alternative runoff channels, temporal 'dormancy' etc.). Functional connections possible also where structure is decoupled.	Firewalls and breaks, established cross scale connections, back-up systems and alternative functionality (e.g. different modes of transportation). Decentralised grids with permanent modularity.	Greater response diversity and partial modularity when functionally connected components only overlap marginally in their properties and functions. More potential options for switching from highly connected/low modularity to less connected/higher modularity.
3. Reorganization				
Managing and facilitating reorganization.	System memory and cross-scale dynamics. Drawing on and guiding multiple 'slow' variables.	Re-colonization and ecological memory. Self-organisation and succession, extended time windows for novelty and change. Low cost and limited predictability.	Strong institutional memory and potentially strong path dependence driven by a need to build back quickly and high investment costs. Opportunity for renewal and innovation.	Guided recovery and restoration, reduced return time to a specific configuration or functional state. Creation of attractors and connections to system memory. Mobilization of a broader suite of assets.
4. Flexibility				
Long term flexibility through promoting alternative functionality and co-benefits .	Learning, inclusivity, public support and engagement, multilayer, polycentric and participative governance.	Open-ended multifunctionality with a broad suite of co-benefits, open to public involvement in management and social learning.	Mobilization and effective use of knowledge and resources. Strong institutions for knowledge creation and sharing. Bricolage, innovation and exploration of new ways of making use of existing structures. Iterative design and maintenance.	Combination of top-down, bottom-up governance. Additional tinkering and multifunctionality by integration of green and grey functionality, partly open to public involvement in management and social learning.

is realized [6]. This article defines resilience as the *capacity of a system to maintain and/or regain function and feedbacks, and its fundamental identity, in the face of shocks or disturbances*. We specifically deal with different qualitative aspects of resilience, that is, mechanisms and emergent qualities of hybridity that may help make functions robust – capable of withstanding or enduring disturbance, up to a threshold – and those guiding and facilitating reorganization after a 'collapse'. As a complement to other studies describing how resilience thinking can be mainstreamed into infrastructure planning and development [3•,22], we focus specifically on the field of design and planning. To help organize and systematize the thinking needed for harnessing the resilience-building potential of hybrid infrastructure, we distinguish four different contributions to resilience—*attenuation, variable connectivity, facilitated reorganization, and flexible multifunctionality*—to capture the different character and dynamics of ecological and engineered systems that offer different and complementary ways of building resilience to new, compounded disturbance regimes (Table 1). Careful design and alignment of the different components in a hybrid infrastructure system can provide multiple, consecutive or complementary layers of resilience that kick in at different magnitudes or frequencies of a disturbances, or at a certain stage of a disturbance cycle. Green and grey components may compensate for each other's weaknesses and help add diversity and flexibility to the system [e.g. Refs. 23,24•]. However, they may also exacerbate the same vulnerabilities and increase the risk for large-scale collapse, or suffer from fragmented governance. Thus, designers need to comprehend both the challenges and the opportunities inherent in hybridity [21,25,26].

Attenuation

Sequential or integrated layers of different grey and green features can reinforce each other, or at least provide additional one-way protection. For example, roofs with high albedo for reflecting sunlight alternated with green roofs for insulation, combined with shading effects from vegetation [27], can be designed to ameliorate extreme heat. In the face of altered disturbance regimes, complementarity through functional diversity, or different *attenuation* effects, is critical for dealing with different disturbances, different combination of disturbances and more extreme magnitudes of disturbances. Different disturbances/weather extremes move or unfold across multiple dimensions depending on the internal mechanisms driving them and contextual factors, such as thermal energy and heat transfer, topography, speed and volume of storm surges [28]. Attenuation is often partial in that any layer of protection primarily affects a particular dimensionality of a disturbance (e.g. breaking waves or increasing diffuse reflection). While redundancy has long been recognized as one of the pillars of resilience, infrastructural 'layers' are not necessarily substitutable. They provide qualitatively different types of resilience or they are activated at different magnitudes of disturbance. In other words, *diversity of attenuation effects is an overlooked counterpart to diversity of responses*. Functionally more diverse layers of protection will thus have complementary and, taken together, more comprehensive effects [e.g. Ref. 29].

Some attenuation layers will be inactive during a relatively mild event and only kick in once a threshold has been passed (potentially/typically marked by the collapse of the 'outer' layers of protection). Attenuation is primarily important for keeping a disturbance away from the city and its critical infrastructures, and most of the benefit of having protective infrastructure in place accrues outside the city. For example, research on coastal protection has

Box 1 Dealing with water: Insights from New Orleans

Extreme flooding is major threat to the world's coastal and riverine cities [50•,51,52]. The highly engineered city of New Orleans represents a possible future condition for population centres along low-lying coasts and deltas, where much of humanity now resides. Following 2005's Hurricane Katrina, the region has rebuilt or retrofitted much of its flood control system, and is increasingly seeing investment in hybrid infrastructure projects. While hybrid approaches have a long history in the area [8], recent efforts have been more explicit about how engineered and ecological systems are anticipated to serve complementary functions [53]. These projects represent one of the most ambitious hybrid infrastructure programs worldwide, incorporating features designed to mitigate and attenuate extreme flooding, manage connectivity, promote multifunctionality and co-benefits to residents, and facilitate reorganization of ecological systems following major disturbances (Figure 2).

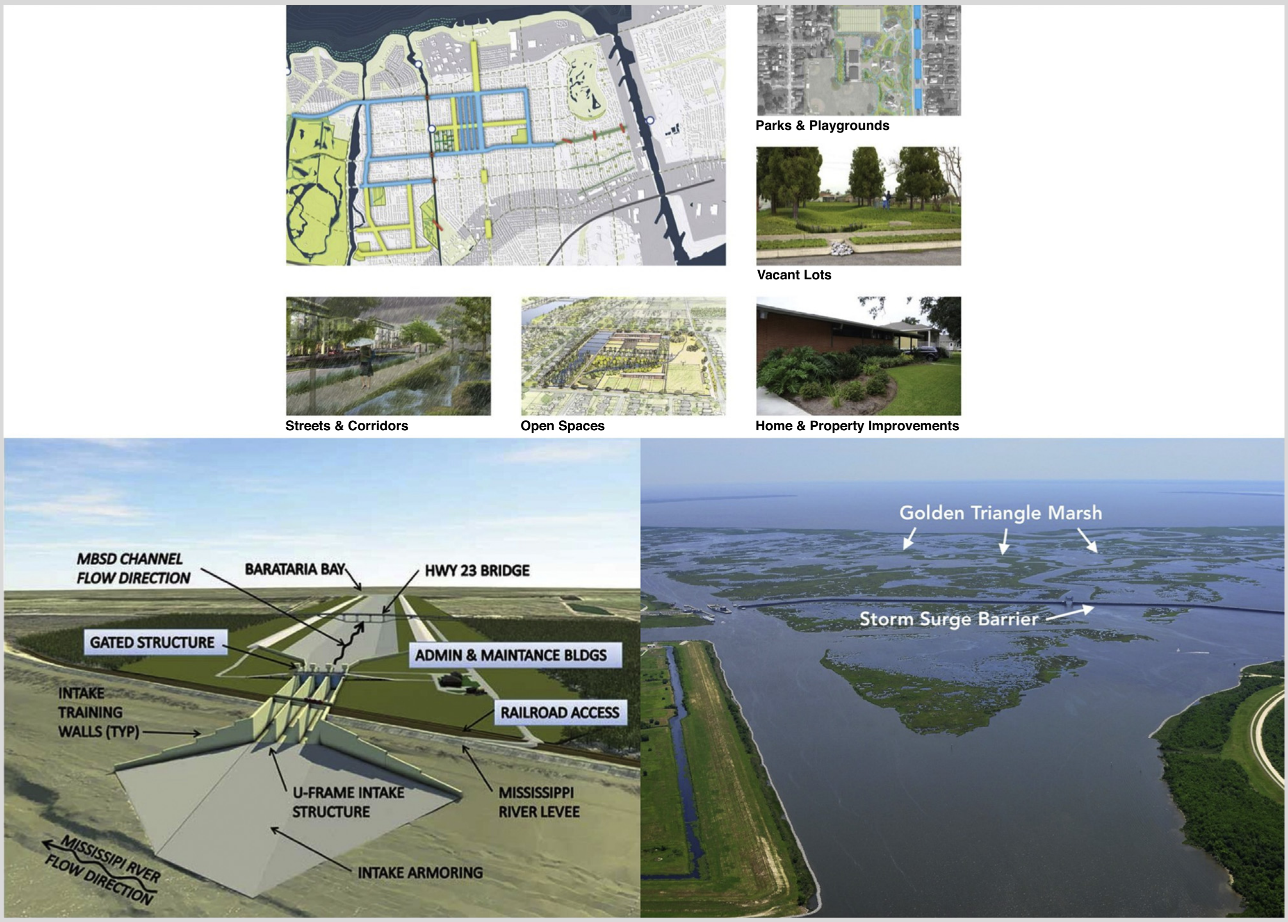
The Golden Triangle Marsh creation project, begun in May 2021, exemplifies how hybrid infrastructures interact with disturbance regimes to attenuate disturbance magnitudes, and manage flows and landscape connectivity patterns. Following the completion of one of the largest storm surge barriers in the world along the city's eastern flank in the 2010s, Louisiana's coastal protection and restoration authority is utilizing dredged sediment to build 3 km^2 of coastal marsh along the new barrier. The marsh is intended to complement the massive storm-surge barrier by attenuating storm surges before they reach the barrier itself. If the surge barrier was breached, a secondary layer of marshes and structural protection within the perimeter system exists to prevent further cascading of flooding into the urban core. Similar marsh and ridge creation projects are planned throughout the region to complement traditional flood protection infrastructure like levees and floodwalls.

Behind these perimeter layers of hybrid protection within the city's urbanized and low-lying core, extreme rainfall remains a threat to residents. Hybrid infrastructures in design and construction within the city aim to capture and redirect stormwater flows to prevent the city's aging and elaborate drainage system from being overwhelmed. These projects use existing greenspace and vacant properties to detain stormwater during intense rainfall events, temporarily storing stormwater until the city's pumping system is back below its maximum capacity. A cluster of these projects in New Orleans Gentilly neighbourhood aims to increase the capacity of the neighbourhood's pumping system by some 30%. These stormwater detainment projects are intended to reduce harm from extreme rainfall events by reducing the magnitude and frequency of street flooding. To do so, they temporally disconnect, or modularize, the drainage systems by a functional 'collapse' of certain parts of the system.

One shortcoming of the Golden Triangle project is that it does not incorporate a mechanism for supplying new sediment inputs into the marsh to sustain it and aid in reorganization following flooding events. Addressing this 'gap', a nearby project on the city's southern edge will utilize a massive diversion structure in the banks of the Mississippi River to divert freshwater and sediment into a degrading marshland. The Mid-Barataria Sediment Diversion is described by planners as the 'largest ecosystem restoration project in the world' because of its capacity to provide up to 2100CMS of water and sediment into Barataria Bay, creating new land in an area that has seen dramatic subsidence and erosion over the past century. Once in place, the diversion structure provides costal planners with a tool for directing sand, sediment, and freshwater in the aftermath of coastal storms. In this way, river diversions will help facilitate reorganization of coastal estuaries following major disturbances.

Multifunctional aspects include flexible recreational use in between disturbances and educational opportunities for learning about infrastructural problems and potential solutions like green infrastructure. These sites are also being utilized for long-term ecological monitoring, to identify potential couplings between infrastructure performance, ecological change, and public health risks, supporting the city's overall goals to enhance environmental systems and resident wellbeing. Taken together, multiple layers of complementary, hybrid infrastructures are nearing full implementation in the New Orleans urban region. The performance of these projects will provide important insights for hybrid approaches globally, especially along urbanized coastlines vulnerable to sea-level rise and flooding.

Figure 2



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Hybrid infrastructure examples in and around New Orleans, USA. Top: Gentilly Resilience District plan in the city of New Orleans, which aims to hybridize neighbourhood drainage through stormwater detainment and infiltration basins in green spaces. *Source: City of New Orleans*. Bottom left: basic design for the mid-Barataria Sediment Diversion, which will mimic natural riverine flooding to mitigate land loss. *Source: Louisiana Coastal Protection and Restoration Authority*. Bottom right: Golden Triangle Marsh, situated on the exposed side of a new storm surge barrier protecting New Orleans. *Source: US Army Corps of Engineers.*

shown how different features can reinforce each other, either by providing complementary mitigating processes (wave attenuation, buffering deep water currents, stopping or channelling overland flows etc.) or by providing multiple layers of the same type of protection [e.g. Refs. 21,29,30] (see Box 1). For another example, absorption of rain or stormwater by small green infrastructure features such as green roofs, rain gardens, or bioswales can reduce the amount and destructive force of stormwater reaching water bodies via stormwater pipe systems (i.e. pluvial flooding) by interception near the origin of flow paths (i.e. rain to roof, roof to garden, garden to street) [31].

Variable connectivity

In addition to more diverse types of external protective layers, hybrid infrastructures also offer opportunities to reduce the harm when a disturbance punches through the outer layers of protection. Infrastructure is by definition connected, and one of the primary functions of infrastructure is to carry and support different flows (e.g. mobility, electricity, cooling). A key infrastructure design and planning challenge involves decoupling disturbance dynamics and flows (un-controlled spread and cascading) from critical connectivity needed for mobility, drinking water, or energy distribution. Thus, managing connectivity is held to be an important aspect of building resilience [12], and we argue that *infrastructure hybridity opens up more options for quickly moving back and forth between connected and modular infrastructure networks*. A shift to a more modular structure where, for example, water flows are intercepted, slowed down and retained in designated features such as raingardens, bioswales, retention basins, detention ponds, or wetlands, offers a way to contain disturbance and avoid cascading. Studies on drainage systems show how decentralised or semi-decentralised (but still functionally connected) solutions have advantages over both centralised systems and point source solutions [32,33••]. Discussing hybrid infrastructure designs, Mangone [33••] argues that 'the relatively smaller scale and cost of semi-decentralized and decentralized infrastructure systems typically renders them more readily able to be integrated into a broader range of landscape and building types and sizes than centralized infrastructure systems' [ibid, pp167]. Modularity can also be achieved by intentionally collapsing part of the infrastructure, diverting flows into some components, or otherwise introducing heterogeneity. These strategies may reduce harm by containing it at more local scales [33••]. Juxtaposed hybrid, internally more diverse infrastructure is also more modular in the sense that the different components are not all functionally similar and thus differ in their responses. Plans for managing risks of fire in urban areas in Australia, developed in response to the devastating large-scale fires in 2019/2020, exemplify a hybrid strategy to reduce the risk of cascading disturbances. This strategy integrates fire risk management into urban planning by promoting modularity in green and grey infrastructure as 'natural' fire breaks, and is augmented further by small-scale indigenous fire management approaches for green modules with high risks [34,35].

Temporary adjustments of the structure and flows of different infrastructures can both help contain damage and stop it from cascading through the system. For example, fortifying lower-risk refuge areas and opening them up for new uses during extreme events strengthens the coping capacity of cities and their inhabitants [21]. However, strategies for changing flows or exposure to disturbances may involve difficult ethical and social justice considerations, so the consequences of managing connectivity for social, ecological, and built components must all be considered [16••].

Facilitating reorganisation

In addition to reducing harm, intentionally collapsing parts of the system and the resultant disruption of subnetwork linkages (while leaving much of the total network intact, if temporarily disconnected) provide spatial resilience and different means to support post-disturbance recovery and reorganisation [cf. 36]. Shifting back from a locally contained or modular system like a metropolitan area (suitable for polycentric governance, administrative ease etc.) to a state with more active connections and flows to larger scales offers complementary ways to initiate and guide the process of bringing infrastructure back to functionality. We have earlier highlighted the challenge of strong urban path dependencies or traditions representing barriers to innovation. Recovery or restoration under these conditions are often driven by deeply engrained practices or power relations where choice of infrastructure may be influenced by interests connected to property and appropriation regimes that do not support hybrid or green infrastructure [25]. Hybridity encourages broader stakeholder involvement and offers opportunities to rebuild not only structure, but sense of place and self-identity [37].

Undisturbed areas can be seen as *repositories and sources of social-ecological-technological 'memory'* [38–40], which may be mobilised and used in different ways. in the form of for example seed banks, undisturbed organismal populations in the larger region, or post-disturbance physical infrastructure, supports the return of function to adjacent areas (when damage is limited) and, manifested as technical and local knowledge, skills and knowhow, guides rebuilding and active restoration (when infrastructure has been too damaged to allow for immediately resuming 'normal' functions). By having green, grey and hybrid infrastructure already in place before disturbances there will be precedents for the combination of two very different processes of reorganisation. Different options, even small-scale experiments, may serve as more tangible seeds for transformation [41,42]. Transition studies have shown that if there is no viable alternative to the dominant infrastructure solution in place at the time of the extreme event, then this event will reinforce and further entrench existing practice and often outdated institutional values [43].

Flexible multifunctionality

Hybrid infrastructures may deal better with yet unknown needs related to simultaneously ongoing and mutually interdependent global sociocultural and climate change. Increasingly dense infrastructural systems, most prominently our cities, see stronger competition for space and resources. Inert safety mechanisms may lose their meaning to people if the frequency of disturbances is low, if the protection is so effective that people do not notice it, or if the effects are indirect [44]. This means that the layers of protection need not only be resilient to the disturbances themselves but also to the state of non-disturbance and competition from other valuable land uses. More diverse infrastructures, especially combinations of green and grey infrastructure have been shown to often be more multi-functional and flexible in their functioning, and to interact more strongly with processes of sense place and community [e.g. Ref. 37]. The biophysical components of hybrid infrastructure have the advantage that they quite often offer additional functions and benefits beyond a primary function [14,24•].

While hybrid infrastructure may have a latent potential for multifunctionality, this is not necessarily recognized or realised [45]. Potential functions, and different ways of realising them, need to be explored and then made legible to the potential beneficiaries. To guide the future design of new urban infrastructure and the redesign of existing structures, management and decisions based on a complex system view an urban tinkering approach might prove helpful [46]. With a diversity of structures to work with and more actors with the prerequisite skills and knowledge to work with them, there are opportunities to recombine, re-imagine and repurpose infrastructures to explore and adapt their functionality to fit different needs and respond to emergent dynamics [3•]. Constant work to keep infrastructures and their functions and uses relevant provides a final layer of resilience by promoting learning, experimentation, and public support and by empowering different actors to be involved. Such resilience building needs to involve a constant interaction between social and natural systems in recognition of that both systems change over time and that these changes include future uncertainties. It needs therefore draw on adaptive approaches that must involve multiple actors and associated institutions in all policy domains [3•,47]. This also involves social learning and empowerment at the level of society, expressed in dynamic institutions and flexible management policies [48]. However, hybrid infrastructure designs will likely not be perceived as functionally equivalent and integrated systems until they have been thoroughly tested with the same level of analytical processes, performance standards, and assessment criteria as more conventional infrastructure [49].

Conclusions

Hybridity in infrastructure design presents opportunities for more complementary ways of building resilience and anticipating novel disturbance regimes. Functionally diverse infrastructural elements can offer diverse attenuation functions, new ways of actively changing infrastructure connectivity, and a broader portfolio of guided but organic reorganisation pathways. Hybridity is also the foundation for generating diverse ecosystem services and deriving wellbeing benefits from them, which could help make both individual elements and complete infrastructure systems directly relevant to urban residents with different needs and interests. This diversity presents both a challenge and an opportunity — more people will need to be involved in the design and maintenance of hybrid infrastructure, which increases the pool of knowledge, competencies, resources and hence emergence of markets for new green jobs, while carrying new governance challenges for coordination and integration. Novelty through hybridity may also offer an opportunity to revisit conventional solutions and challenge the assumptions and potential simplifications potentially built into them. Consideration of complementary attenuation, variable connectivity, facilitated reorganisation and explorative, flexible use and management is critical for understanding and responding to the novel disturbance regimes brought on by climate change, taking on the immense challenge of climate adaptation.

Conflict of interest statement

Nothing declared.

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