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Reducing disaster risk for the poor in tomorrow's cities with computational science

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Rapid urban expansion presents a major challenge to delivering the United Nations Sustainable Development Goals. Urban populations are forecast to increase by 2.2 billion by 2050, and business as usual will condemn many of these new citizens to lives dominated by disaster risk. This need not be the case. Computational science can help urban planners and decision-makers to turn this threat into a time-limited opportunity to reduce disaster risk for hundreds of millions of people.

Globally, rapid urban expansion is transforming countless lives. The United Nations Human Settlements Programme has forecast that by 2050, 2.2 billion more people will live in urban centres worldwide and that 95 per cent of this growth will be in the Global South[1]. More specifically, growth in urban population is predicted to increase by some 25 per cent in developed regions, contrasting with forecast growth of more than 600 per cent for the least developed countries[2].

This historically unprecedented urbanization could potentially produce a commensurate increase in disaster risk induced by natural hazards. It is estimated, for example, that the number of people exposed to devastating earthquakes will more than double to over 800 million by 2050. Similarly, hundreds of millions of people will be increasingly threatened by floods and cyclones, amplified by accelerating climate change[3]. The United Nations Office for Disaster Risk Reduction has highlighted[4] how disaster risk affects 25 Sustainable Development Goal (SDG) targets in 10 of the 17 SDGs. The systemic and mutually reinforcing impacts of disasters connect to the other SDGs through a short chain of cause and effect. Three of the goals are most explicitly related to disaster risk: SDG1 (No Poverty), SDG11 (Sustainable Cities and Communities) and SDG13 (Climate Action). All three SDGs aim to improve coordinated planning and decision-making by, for instance, adopting and implementing local-government-led strategies for disaster risk reduction that align with national policies.

The economically poor and politically marginalized are disproportionately affected by disasters[5]: they have limited capacity to withstand and recover from physical and socioeconomic shocks. A vicious cycle ensures that the poor, often living in high-risk areas, experience amplified disaster impacts; their economically marginal status depresses resilience to disaster-driven systemic economic shocks, which revert economic progress, leading to greater marginalization, inevitably generating deeper poverty and greater disaster risk.

The current juxtaposition of hazard vulnerability and global urbanization concentrated in the least developed countries and the intensifying climate emergency superimposed on the background disaster risk (from earthquakes and landslides, for example) condemns hundreds of millions of people to a future dominated by poverty and disaster risk. Without concerted action, this dystopian future will become a reality in the next two to three decades.

Of course, urbanization also presents a clear opportunity to prevent the downward spiral described above by deploying large-scale disaster risk management of new urban development to stabilize the economic future for new urban populations. Reducing disaster risk reduces poverty, which in turn reduces disaster risk[6]. Forecast global demographic models have put a clock on this opportunity; it substantially evaporates by 2050. Within the next 30 years, risk-sensitive urban planning and decision-making for new urban development must not only reduce disaster risk by promoting resilient physical infrastructure, but must also include the perspective of marginalized groups in planning. Such inclusion will catalyse equitable access to basic needs and welfare and move past existing inequalities, helping to break cycles of exclusion, hazard exposure, vulnerability and loss.

The Tomorrow's Cities Hub, funded by the UK Research and Innovation (UKRI) Global Challenges Research Fund (GCRF) Intractable Challenges Programme, provides a forward-looking, pro-poor perspective that orients interdisciplinary science towards questions of future urban development in places already exposed to natural hazards and climate change[7]. It shifts the narrative from managing only today's disaster risk to building cities to avoid hazard exposure, reduce vulnerabilities and increase resilience — especially for the urban poor, the majority of those who live in the most rapidly expanding cities.

Although earthquakes, for example, are natural processes, seismic disasters result from human choices. With a clear focus on this basic truth, the Hub has developed a pro-poor, risk-sensitive urban planning agenda. Computational research sits at the centre of this work and is critical in bringing this agenda to life, reducing risk in as-yet-unbuilt communities (here, we consider both infrastructure and population) by optimizing decision-making for inclusive disaster risk reduction. By understanding the consequences of today's decisions on tomorrow's disaster risk before we commit to policy change and construction, such research can facilitate more capable governance supported by evidence-based, low-risk choices today that can change the future for millions of people over the next decades.

The critical role of computational science

Computational science, including numerical simulation through high-performance computing, data analytics and visualization,

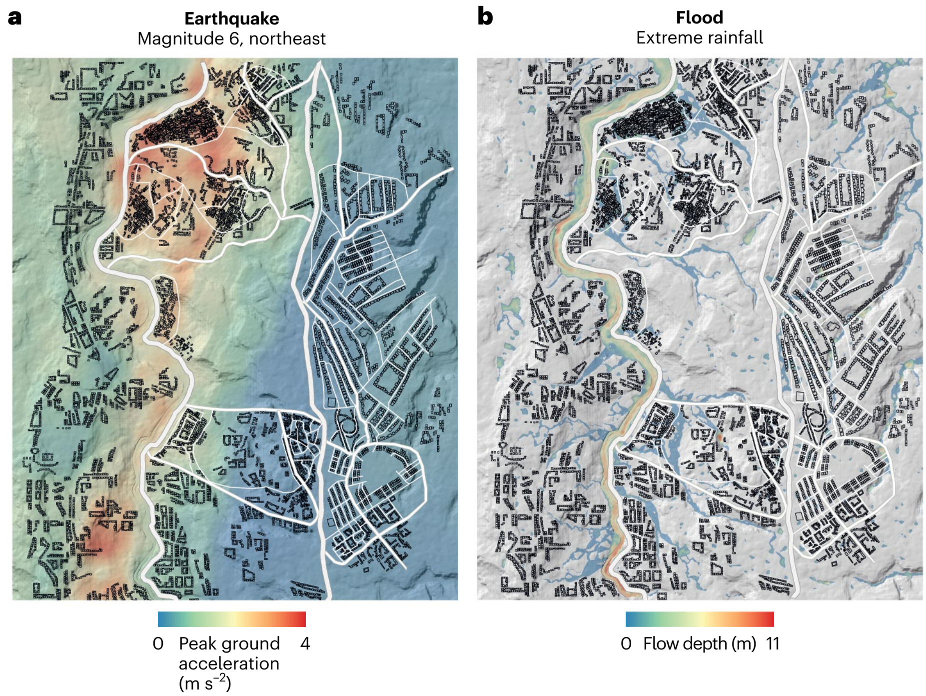

Fig. 1 | Building resilience to disasters using a virtual city, Tomorrowville. Disaster reduction programmes often depend on externally developed solutions imposed on specific local challenges. Computational science provides digital tools that can support innovative capacity strengthening, freeing possible futures thinking from the responsibility for real lives and encouraging experimentation with innovative planning solutions. **a, b**, Here, the virtual city of Tomorrowville is shaken by a virtual earthquake (**a**) and flooded by a virtual extreme rainfall event triggered by climate change (**b**), exposing spatial variability in exposure and driving reconsideration of spatially uniform building regulations. Q7

can underpin the SDGs. This is especially true when deployed in collaboration with other scientific domains and as part of co-produced knowledge-generation processes with a range of urban stakeholders and end users. By acknowledging the systemic nature of the causes of disasters, such research must facilitate the inclusive engagement of scientists, engineers, policy-makers, economists, private sector groups and, critically, representatives of the citizens who will live in the cities experiencing rapid growth. The SDGs recognize that urban development plans made today will either brighten or blight the lives of citizens for centuries.

A three-part agenda for interdisciplinary science marks out how computational science can be used to underpin and catalyse this ambition. Each step in the agenda can stand alone or together form a structured process from better understanding to better action to reduce disaster risk in future cities.

(1) **Digitally capturing inclusive future visions**

Many social science methodologies are available with which to plan preferences for neighbourhood or city-wide futures. A challenging task is enabling such methodologies to capture the subjective visions of the future of diverse urban stakeholders. Only by doing this can future cities disrupt established norms and consider what a safer city of the future looks like from different or multiple perspectives. Such methodologies are difficult to translate into policy options; they are often qualitative and can appear imprecise to policy-makers. However, such qualitative information has a huge potential to act as a basis for future urban scenario development if it can be assimilated into precise digital representations. Computational science can help here. Spatial components of the projections (such as desired land-use zones and their attributes) can be translated into land-use plans using geographic information systems and related computational tools. This information can be complemented with predicted patterns of urban growth, determined using machine learning algorithms that rely on remote sensing data. Spatial priorities emerging from stakeholder groups are thus rendered into high-resolution digital representations of possible urban futures[8].

Such digital future cities also incorporate detailed attributes of people and assets. These include engineering characteristics for each building and infrastructure component and system, information on socio-demographics for each individual and household, and data on socio-physical interdependencies (for instance, where each person goes to work and where each child goes to school). The virtual representation is achieved using several computational models, including synthetic population-generation algorithms, human mobility methods, procedural modelling and optimization processes[viii]. Q6

(2) **Exposing digital futures to likely hazard events**

The high-resolution virtual representations of possible future urban developments must be exposed to hazard events that are consistent with the hydrological and geophysical environment of the city. A series of hazard events can be selected to cover possible life-cycle experiences of the development. A key effort in the Tomorrow's Cities project, for example, has been to code these events into high-resolution, physics-based simulations[9] (Fig. 1), taking advantage of the latest developments in high-performance computing. A custom-developed web-based application merges site-specific intensity data from the hazard event with exposure and vulnerability information in the future development scenario to compute the likely impact of any particular event. These calculations use several underlying computational tools, including high-resolution, multi-hazard fragility models developed from detailed building-level numerical performance assessments[10] and data-mining models that can distinguish the magnitude of disaster impacts on the basis of social vulnerability indicators[11,12]. Agent-based modelling is another powerful approach in the field of disaster simulation that allows researchers to simulate the dynamic behaviour of individual entities (agents), with their socio-economic features, within a complex system.

Depending on the particular scenario, multiple impact metrics reflecting diverse aspects of the lived experience (for instance, number of deaths, number of displacements, number of injuries, hospital occupancy, lost days of production or school and total replacement costs) can be calculated and mapped, providing a detailed picture of the total impact of any disaster event resulting from the decisions and policies that generated the specific digital future being tested. Each of these metrics can be disaggregated in different ways, including by age, gender, income or any other attribute contained in the demographic dataset of the virtual future representation, providing an understanding of the consequences of the decisions made during planning and scenario building.

To complete the picture of the root causes of disaster impact for policy-makers, quantifying and mitigating social vulnerability (the susceptibility of an individual from a given group to the impacts of hazards) can help to build resilience to multiple types of hazard shock. So far, there is a dearth of disaggregated data recording disaster impacts and social vulnerability measures simultaneously, and the current priority is to collect longer data series. These might emerge, for example, from satellite remote sensing; computational methods in unsupervised learning and data clustering as well as deep learning (for instance, neural networks) could then be leveraged to refine quantitative modelling of social vulnerability. Exploring nonlinear and multi-scalar relations between exposure, vulnerability and disaster impacts is an important research ambition[13].

(3) **Convening risk agreement and institutional learning**

Impact is objective, but risk depends on personal or group priorities; the value of property replacement, for example, has a different priority depending on whether or not you own property. Computational science supports interactive representations of complex urban impact scenarios, facilitating the quantification of subjective risk priorities by generating impact-weighting matrices that include the voice of marginalized groups in the local definition of disaster risk. Equipped with weighted risk definitions, attention turns to exposing the root causes of such risk in the choices and decisions behind any development plan. Dynamic digital visualizations of the impact metrics produced by simulation-based tools could help to elucidate the distribution of risk inherent in development planning and to diagnose risk drivers, inverting complex causal chains and exposing the underlying flaws in decision-making. In the case of the Tomorrow's Cities Hub, this is communicated to stakeholders through their web-based application. More formal inversions uncovering root causes from impact metrics are needed to clarify the diagnosis and reinforce evidence-based decision-making for risk reduction.

Focusing on the origins of risk in the decisions, policies and assumptions underpinning future development scenarios allows stakeholders to examine their choices and reflect on broader governance questions. Modifications to particular stakeholder priorities that are likely to lead to reduced risk are implemented in the digital development scenarios. These are then subjected to the same simulated hazard events to test the resulting risk reduction. The process is iterated, optimizing the future for lower risk, elucidating the effectiveness of governance processes and supporting evidence-based decision-making.

Conclusion

Science tends to leave policy-makers with recommendations that can quickly be overwritten by the next political priority or enticing research project, potentially making the coupling between policy-making, inclusion and science a transient one. The progress and challenges outlined above emphasize how science, leaning heavily on computation, can be embedded within wider knowledge generation and analysis frameworks that prioritize inclusion and transparency, leading to accountable decision-making. From stakeholder-led planning that includes marginalized voices to the digital simulation of infrastructure, demography, vulnerability and hazard events, science can provide pathways to futures of reduced risk. In this vision, computational science escapes its traditional silos of modelling and visualization to play a central part in a dynamic research agenda that prioritizes engagement and action planning over existing dominant development paradigms and voices.

The agenda outlined here aims to encourage the computational science community to address the SDGs by placing computational science in interdisciplinary contexts and as part of ongoing conversations with multiple stakeholders. The approach is inspired by the experience of the Tomorrow's Cities project but reaches far beyond. By bringing together local at-risk populations and local and national governments to collaborate in future risk reduction, this agenda demonstrates how computational science can help to build equity and resilience into cities of the future, today.

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Competing interests
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