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Digital Twins, Predictive Infrastructure and Resilience: A Theoretical Framework for Asset Management and Climate Adaptation in Infrastructure-Deficit Cities

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ABSTRACT

Digital twins, continuously updated computational models of physical infrastructure, allow cities to predict failures, simulate interventions and plan for climate stress, and they are being promoted to African cities facing both an infrastructure deficit and intensifying floods, heat and storms. This theoretical paper asks what predictive infrastructure management offers a city whose problem is not the degradation of assets it has but the absence of assets it needs. Drawing on infrastructure-studies and asset-management theory, on the urban-resilience and climate-adaptation literatures, and on recent research on digital twins and artificial intelligence in infrastructure, it distinguishes three decision problems, maintaining existing assets, prioritising new investment, and responding to acute events, and shows that digital twins are strongest on the first, which is the least pressing in infrastructure-deficit cities, and weakest on the second, which is the most. The paper develops a framework for predictive infrastructure under deficit conditions in which the value of modelling lies in investment prioritisation and in drainage, flood and heat planning rather than in asset optimisation; derives seven propositions about the data, institutional and financial conditions under which such systems improve resilience; and examines the risk that twin-driven investment favours the already served. Flood-exposed Lagos anchors the analysis. The paper closes with implications for city governments, infrastructure financiers, vendors and the research agenda of African urban infrastructure studies. It concludes that the decision a deficit city most needs to improve is not how to maintain the assets it has but what to build, for whom, before the next flood, and that a predictive model reoriented toward that decision, less a replica of the city than an honest estimate of its hazards and needs, would be the first such tool built for the cities that need it most.

Keywords: digital twins; infrastructure; asset management; predictive maintenance; urban resilience

Digital Twins, Predictive Infrastructure and Resilience: A Theoretical Framework for Asset Management and Climate Adaptation in Infrastructure-Deficit Cities

1. INTRODUCTION

The digital twin has become the most ambitious object in the smart-city vocabulary. Where earlier systems collected data about a city, the twin promises a living model of it: a computational replica of roads, bridges, drains, pipes, cables and buildings, fed by sensors and updated continuously, on which engineers can detect deterioration before it becomes failure, simulate interventions before committing to them, and rehearse the city's response to flood or heat before the event arrives. The literature tracing the concept's lineage from urban modelling and geographic information systems through the smart city to the twin city with artificial intelligence presents it as the culmination of a long project to make the city computable (Yeh, 2024). Reviews of its application to civil infrastructure document rapid growth across sectors, phases and scales (Liu et al., 2023; Kookalani et al., 2026), and the promise is now being extended to African cities as part of the broader push for artificial intelligence in urban governance (Mhlanga, 2026; Egba et al., 2026).

The cities to which the promise is extended have a problem the twin was not designed to solve. Their infrastructure is not primarily deteriorating; it is absent. Drainage systems do not reach most of the settlements that flood. Roads are unpaved, bridges few, water and power networks partial. The urban periphery, where most growth is occurring, is being built without the assets a twin would model (Büttner et al., 2025). At the same time, climate hazards are intensifying: floods, heat and storms fall on cities with the least capacity to absorb them, and the burden falls hardest on informal settlements built on the land no one else wanted (Sinore & Wang, 2025; Buyana & Sseviiri, 2026; Bhanye, 2026). The question this paper addresses is what predictive infrastructure management can offer under these conditions, when the asset base is thin, the hazard is rising and the institutions responsible are weak.

The paper's argument is that infrastructure management comprises three distinct decision problems, maintaining the assets a city has, prioritising the investment it needs, and responding to the acute events it faces, and that digital twins as currently developed are strongest on the first and weakest on the second, while cities under infrastructure deficit face the second most urgently. From this mismatch it develops a framework for predictive infrastructure under deficit conditions in which modelling is reoriented from asset optimisation toward investment prioritisation and hazard planning, derives propositions about the conditions under which such systems improve resilience, and examines the distributional risk that twin-driven investment follows the data to the places already served.

The analysis opens with the digital-twin concept and the critical literature that has grown around it, and then characterises the infrastructure-deficit city and its exposure to climate hazard. It develops the three-problem decomposition before presenting the framework and the propositions that follow from it, and it gives separate attention to the distributional risk that twin-driven investment follows the data to the places already served, before applying the framework to flood-exposed Lagos and drawing out its implications.

2. LITERATURE REVIEW

2.1 The Digital Twin and Its Critics

What a digital twin is

A digital twin of infrastructure is a computational model of a physical asset or system that is linked to its physical counterpart by a flow of data, so that the model's state tracks the asset's state over time and can be used to predict its future state and to test interventions. Liu et al. (2023), reviewing digital-twin technologies for civil infrastructure, identify the components that recur across applications: a geometric and physical model, sensing that updates the model, analytics that infer condition and predict deterioration, and interfaces through which engineers interrogate and act on the model. Kookalani et al. (2026), mapping applications across research types, methods, sectors, phases and scales, find the field concentrated on the operation and maintenance phase of built assets and on the asset and facility scale, with city-scale and planning-phase applications less developed. Liu et al. (2025) review modelling approaches and applications specifically in urban infrastructure operations and maintenance and find the same emphasis: the twin is above all an instrument for managing what exists. Jafari et al. (2023), surveying digital twins in smart grids, transport and smart cities, list the challenges that remain, data quality, interoperability, computational cost, security and

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the gap between laboratory demonstration and operational deployment.

The urban digital twin

At city scale the concept becomes both more ambitious and more contested. Patel et al. (2024) review the potential contribution of digital-twin technology to sustainable urban development, finding promise for planning, infrastructure and disaster management alongside unresolved questions of data governance and institutional capacity. Park et al. (2024) propose a participatory framework for urban pluvial flood modelling in what they call the digital-twin era, arguing that flood models at city scale must incorporate local knowledge and stakeholder input rather than relying on sensing alone. Kim et al. (2025) demonstrate a stormwater digital twin with online quality control that detects urban flood hazards under uncertainty, showing that the technology can work for drainage systems where sensor data is noisy and incomplete. Shen and Zhou (2026) propose a hazard-responsive digital twin oriented to weather-driven urban resilience and affordability, extending the concept from asset condition to the resilience of households. Ghaffarian (2025) goes further, proposing a digital risk twin for disaster risk management that integrates automated sensing with manual data collection, surveys, field observation, and keeps a human in the loop of decision, precisely because disaster contexts defeat fully automated models.

The critical turn

A critical literature has formed quickly. Ahn et al. (2025) call for a critical urban informatics of digital-twin models, arguing that the twin's claim to replicate the city conceals choices about what is modelled, for whom and to what end. Marvin et al. (2026) describe digital-twin cities as a form of capitalised urban prototyping that simplifies the city into what can be modelled and traded, privileging the interests of the technology vendors and the infrastructure financiers who commission the models. De Jaeger and Swerts (2026), examining citizen participation in Rotterdam's urban digital twin, find what they call limits by design: the twin's architecture determines in advance what citizens can see, question and change, and the limits are set by the model's builders rather than by democratic choice. These critiques are developed for cities of the Global North. They apply with greater force where the asset base the twin models is thin and the population it leaves out is the majority, the condition the next section describes.

2.2 The Infrastructure-Deficit City Under Climate Stress

Deficit, not deterioration

The defining condition of most African cities is infrastructure deficit rather than infrastructure deterioration. Reviews of smart-city prospects in Africa consistently identify infrastructure deficits, finance and institutional capacity as the binding constraints (Das et al., 2026; Bandauko & Nutifafa Arku, 2023), and the deficit is concentrated where the population is growing fastest. Büttner et al. (2025), mapping slums across 529 major sub-Saharan African cities at ten-metre resolution, find strong slum growth in the urban periphery between 2016 and 2022: the city is expanding into territory that has no drainage, no paved roads and no networked services, and that will not acquire them on any planned schedule. Borofsky et al. (2025), setting a research agenda on infrastructure in informal settlements, emphasise that the data gap is as severe as the infrastructure gap and that the two reinforce each other: what is not built is not measured, and what is not measured is not planned for.

Hazard on the periphery

Climate hazard falls on this deficit. Sinore and Wang (2025), systematically reviewing climate-change impacts and adaptation options in sub-Saharan Africa, document intensifying floods, droughts and heat and a widening gap between adaptation need and adaptation action. Buyana and Sseviiri (2026) argue that adaptation governance in African informal settlements must be transformed because existing arrangements assume formal planning, tenure and service systems that the settlements lack. Hugo (2023) documents heat-stress adaptation measures in South African informal settlements, where housing materials, density and the absence of shade and cooling make residents far more exposed than the formal city. Bhanye (2026), comparing flood adaptation in thirteen informal settlements across Africa, Asia and Latin America, identifies infrastructures of exclusion, planning by omission and partial participation, that stratify resilience, and Castro (2026) shows how informal waterfront communities in Lagos build their own adaptation infrastructures, which state demolition then destroys. Mwenje and Kumar (2024), examining the mainstreaming of climate adaptation in Kigali, find that even a city with unusual planning capacity struggles to translate adaptation intent into infrastructure decisions, and

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Peroni and Pappalardo (2024) argue that climate justice in future cities requires adaptation that is inclusive by design rather than by afterthought.

The data condition

The infrastructure-deficit city is also a data-deficit city. Hughes and Lawrence (2024), working on hydrological modelling in data-scarce regions of southern Africa, show that sound practice requires explicit, realistic uncertainty bounds because the observational record cannot constrain models tightly; the point generalises to every model a twin would run. Sensors are few; historical records of asset condition are absent because the assets are recent or informal; and the hazard record is incomplete, as Dossa et al. (2025) note in examining the relationship between urban expansion and flood occurrence in Lagos from international databases rather than local monitoring. A digital twin in this setting cannot be fed; it must be built from sparse, uncertain and partly manual data, which is the condition Ghaffarian's (2025) digital risk twin was designed to address.

Together these characteristics define the problem. The twin is an instrument for managing an existing, sensed asset base against gradual deterioration. The infrastructure-deficit city has a thin, largely unsensed asset base and faces acute hazard. What the twin does best is not what the city most needs.

3. CONCEPTUAL FRAMEWORK

3.1 Three Decision Problems

Infrastructure management can be decomposed into three decision problems that call for different information, different institutions and different kinds of model.

Maintaining what exists

The first problem is to keep an existing asset in service: to detect deterioration, predict failure and schedule intervention at least cost. This is the home ground of the digital twin and of the structural-health-monitoring and predictive-maintenance literatures that preceded it. Sonbul and Rashid (2023), systematically reviewing algorithms and techniques for the structural health monitoring of bridges, show the maturity of signal processing and machine learning for inferring condition from sensor data. Liu et al. (2025) and Kookalani et al. (2026) show that the great majority of infrastructure digital-twin applications address this phase. The problem presupposes an asset worth maintaining, sensing that reports its state, and a maintenance organisation that acts on predictions. In infrastructure-deficit cities the first condition holds for a minority of assets, major bridges, trunk roads, power plants, water-treatment works, and the second and third hold rarely.

Prioritising what to build

The second problem is to decide, among the many assets a city lacks, which to build first, where and to what standard, under a budget that cannot fund them all and a hazard that is changing. This is the dominant problem of the infrastructure-deficit city and the one on which the digital twin is weakest, for a structural reason: a twin models what exists, and the investment problem concerns what does not. Models can help, simulating the flood-reduction benefit of a drainage line that has not been built, the accessibility gain of a road, the heat reduction of tree cover, but these are planning models, not twins, and Kookalani et al. (2026) find the planning phase and the city scale under-represented in the digital-twin literature. The investment problem also has a distributional dimension that the maintenance problem lacks: whom to serve first. Mwenje and Kumar (2024) and Peroni and Pappalardo (2024) show that this choice is political before it is technical and that adaptation planning tends, unless designed otherwise, to serve the formal city.

Responding to acute events

The third problem is to act during and immediately after an event: to warn, evacuate, reroute, pump, repair. Here the digital twin has a genuine and growing contribution. Kim et al. (2025) show that a stormwater twin with online quality control can detect flood hazards under uncertainty; Park et al. (2024) show that participatory flood modelling can integrate local knowledge; Shen and Zhou (2026) extend the twin to household-level resilience and affordability under weather hazard; Ghaffarian (2025) adapts the concept for disaster risk management with human-in-the-loop decision. The response problem does not require a complete asset model; it requires a hazard model, a map of exposure and a channel to those exposed. These can be built with sparse data, and their value is highest exactly where the asset base is thinnest, because the population that floods is the population without drainage.

The mismatch

The decomposition yields the paper's central diagnosis. Digital twins are strongest on maintenance, intermediate on response and weakest

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on investment prioritisation. Infrastructure-deficit cities need investment prioritisation most, response urgently and maintenance least, not because maintenance is unimportant but because there is comparatively little to maintain. A city that adopts the twin as marketed will acquire a sophisticated instrument for the smallest of its problems. The remedy is not to reject the technology but to reorient it, which is the task of the framework that follows.

3.2 A Framework for Predictive Infrastructure Under Deficit

Reorientation

The framework reorients predictive infrastructure modelling in deficit cities around two uses: investment prioritisation and hazard planning. For investment prioritisation, the model's purpose is to estimate, for candidate assets that do not yet exist, their expected contribution to resilience, access and welfare under plausible hazard scenarios, and to make the distributional consequences of each candidate visible. For hazard planning, the model's purpose is to represent flood, heat and storm exposure at the resolution of the settlement and the household, to identify the populations most exposed, and to support warning and response. Asset optimisation, the twin's native function, is retained for the minority of assets that warrant it and is explicitly subordinated to the other two.

Data strategy

A deficit city cannot sense its way to a twin. The framework therefore adopts the hybrid data strategy that Ghaffarian (2025) proposes for disaster risk and that Park et al. (2024) propose for flood modelling: automated sensing where it exists and is affordable, remote sensing for the periphery that has no sensors, community-generated data, enumeration, participatory mapping, reporting, for exposure and for the informal infrastructure that residents have built (Castro, 2026), and explicit uncertainty bounds of the kind Hughes and Lawrence (2024) insist on wherever the observational record is thin. The twin becomes less a replica than a structured estimate, honest about what it does not know.

Institutional placement

The framework places the model within the institution that makes investment decisions, the planning and budgeting function of the state or city government, rather than within the maintenance organisation where vendors naturally install it. This placement follows from the diagnosis: the problem the model must serve is prioritisation, and prioritisation is a budget decision. It also follows from the critical literature: Marvin et al. (2026) and De Jaeger and Swerts (2026) show that where the model sits determines whose questions it answers, and a twin owned by an asset manager will answer asset-management questions. Human-in-the-loop decision, which Ghaffarian (2025) builds into the digital risk twin, is a design requirement rather than an option, because the prioritisation problem is political.

Propositions

Proposition 1. In cities where the share of infrastructure that is absent exceeds the share that is deteriorating, the resilience return on predictive modelling is higher for investment prioritisation and hazard planning than for asset optimisation, and procurement that leads with asset optimisation will underperform. Proposition 2. The value of a digital twin for hazard response is inversely related to the completeness of the asset base it models, because the populations most exposed to flood and heat are those without the assets that would protect them, and a hazard model that reaches them delivers more than an asset model that does not. Proposition 3. Models built on automated sensing alone will systematically under-represent the periphery and the informal settlement, and will therefore misallocate attention and investment toward the sensed formal city; hybrid data strategies that include remote sensing and community-generated data correct the bias in proportion to their coverage. Proposition 4. Predictive models placed within maintenance organisations will be used for maintenance; placed within planning and budgeting functions they will be used for prioritisation; the institutional placement, not the model's capability, determines its use. Proposition 5. The resilience benefit of predictive infrastructure depends on the capacity of the responsible institution to act on predictions, to fund, build, pump, warn, and where that capacity is absent additional prediction produces additional unacted-upon knowledge; the finding recurs across the adaptation literature on African cities (Mwenje & Kumar, 2024; Buyana & Sseviiri, 2026). Proposition 6. Twin-driven investment will, absent explicit distributional constraints, favour the areas with the most data, the highest asset values and the most articulate stakeholders, which are the areas already best served; distributional outcomes must be a model output, not an afterthought. Proposition 7. Where models carry explicit uncertainty bounds, decision-makers will make more robust investment choices than where models present point

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predictions, because deficit-city investment decisions are made under deep uncertainty about hazard, growth and institutional performance; the discipline that Hughes and Lawrence (2024) prescribe for hydrology applies to the twin.

The propositions are stated so as to be testable through comparative case study, simulation and evaluation of deployments. Together they specify the conditions under which a digital twin improves rather than merely describes the resilience of an infrastructure-deficit city.

4. ANALYSIS AND DISCUSSION

4.1 The Distributional Risk

The gravest risk of digital twins in deficit cities is not that they fail but that they succeed for the wrong people. The mechanism is simple. A twin is built from data, data comes from sensing, sensing is installed on assets that exist and are valued, and such assets are concentrated in the formal city. The model therefore sees the central business district, the trunk roads, the gated estates and the industrial zone in detail and the informal periphery barely or not at all. Investment guided by the model follows the model's vision. The result is that the technology marketed as making cities resilient makes the already-resilient parts more so while leaving the exposed parts as they were, or worse, because the capital spent on the twin and its recommendations was capital that could have built drains.

The critical literature has anticipated the mechanism in principle. Ahn et al. (2025) ask what the twin models and for whom; Marvin et al. (2026) show that the twin simplifies the city into what capital can model and finance; De Jaeger and Swerts (2026) show that the twin's limits are set by design. In deficit cities the mechanism is sharper because the unmodelled population is the majority and the hazard it faces is acute. Bhanye's (2026) infrastructures of exclusion, planning by omission, acquire a computational form: omission from the model becomes omission from the plan. Buyana and Sseviiri (2026) and Hugo (2023) show that informal settlements have adaptation needs that formal planning does not recognise; a twin built on formal data will not recognise them either.

The framework addresses the risk in three ways. It makes distributional outcomes an explicit model output, so that any investment recommendation is accompanied by an account of who gains. It mandates hybrid data so that the periphery is represented, following Park et al. (2024) on participation and Castro (2026) on informal infrastructure. And it places the model in the budgeting function with a human in the loop, so that the political choice of whom to serve is made by people accountable for it rather than embedded silently in a sensor layout. None of this guarantees equitable investment. It guarantees that inequitable investment cannot be attributed to the model.

4.2 Lagos as an Anchoring Case

Lagos is the paradigmatic infrastructure-deficit megacity under climate stress. Its population is variously estimated at between eighteen and twenty-five million; a large share lives in informal settlements, many on the lagoon and the Atlantic waterfront; and flooding is annual, worsening and unevenly distributed (Shadare, 2026). Dossa et al. (2025) find that urban expansion and flood occurrence have moved together in Lagos and argue that flood resilience must be rethought in terms of spatial equity, because the expansion has occurred in the areas most exposed and least drained. Castro (2026) shows that waterfront communities build their own adaptation infrastructures and that state demolition destroys them. Shadare (2026) finds that governance responses to compound climate and displacement risk have amplified rather than reduced vulnerability, with waterfront redevelopment, Eko Atlantic among them, displacing the exposed rather than protecting them.

What a twin would see

A digital twin of Lagos built as marketed would model the Third Mainland Bridge, the Lekki–Epe corridor, the bus rapid transit lanes, the port access roads, the formal drainage of Victoria Island and Ikoyi, and the power and water networks that serve the formal city. It would detect deterioration in these assets and schedule their maintenance. It would not model Makoko, Ajegunle or the hundreds of settlements on the periphery that flood each rainy season, because they contain no sensed assets, and it would therefore have nothing to say about the investments, drainage, embankments, raised roads, early warning, that would most reduce the city's flood losses. Proposition 2 and Proposition 6 apply directly: the twin's value for response is inversely related to the asset base it models, and its investment recommendations would follow the data to the places already served.

What a reoriented model would do

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A model built on the framework would start from hazard rather than assets. It would combine the remote-sensing coverage that Büttner et al. (2025) show is now available for the whole periphery with community-generated exposure data of the kind the Nigerian Slum/Informal Settlement Federation already collects, with the flood records that Dossa et al. (2025) assemble, and with explicit uncertainty bounds. Its primary outputs would be a ranking of candidate drainage, embankment and access investments by expected flood-loss reduction and by the population served, with distributional consequences shown; a settlement-resolution exposure map supporting warning and response; and, for the minority of major assets, a conventional maintenance twin. It would sit in the Lagos State planning and budgeting function, not in the maintenance department of a single agency, and its recommendations would be decided by accountable officials. Whether Lagos builds such a model depends, as Shadare (2026) and Castro (2026) make clear, on whether the state's purpose is to protect the exposed or to redevelop the land they occupy. The framework cannot settle that question. It can ensure that the model does not settle it silently.

4.3 Implications

For city governments

City governments in deficit conditions should specify, before procuring any digital twin, which of the three decision problems it is to serve, and should decline systems whose architecture serves maintenance when the city's problem is investment. They should require hybrid data strategies that represent the periphery, explicit uncertainty bounds, distributional outputs and placement within the planning and budgeting function. And they should recognise that the model's resilience benefit is bounded by their own capacity to act, so that investment in the model should be matched by investment in the drainage crews, warning systems and budget lines that act on it.

For financiers and development partners

Infrastructure financiers and development partners increasingly fund digital twins as a component of resilience lending. The framework suggests that such funding should be conditional on the reorientation described here, and that the distributional outputs of the model should be a reporting requirement, so that resilience finance can be shown to reach the exposed rather than the already served. Marvin et al.'s (2026) warning that the twin capitalises urban futures for its financiers is a warning to financiers as much as about them.

For vendors

The digital-twin industry has built its products for asset-rich cities and sells them to asset-poor ones with little modification. The market opportunity in deficit cities lies in the reoriented model, hazard-first, hybrid-data, prioritisation-oriented, uncertainty-aware, and vendors that build it will find both a larger market and a defensible claim to resilience benefit. Ghaffarian's (2025) digital risk twin and Park et al.'s (2024) participatory flood framework are early designs in this direction.

For research

The propositions can be tested. Comparative evaluation of twin deployments in cities with different asset-base completeness would test Propositions 1 and 2. Comparison of models built on sensing alone with hybrid-data models, assessed against independent exposure surveys, would test Proposition 3. Institutional case studies of where models are placed and how they are used would test Proposition 4. Decision experiments comparing point-prediction and uncertainty-bounded presentations would test Proposition 7. The distributional outcomes of twin-driven investment, which Proposition 6 predicts, are observable in budget allocations and should be tracked. And the Lagos case needs the peer-reviewed infrastructure literature it has largely lacked.

Limits

The framework is conceptual and does not evaluate any deployed system. It treats the three decision problems as separable when real decisions combine them. It is built from a digital-twin literature that is overwhelmingly Northern and an African adaptation literature that is concentrated in a few cities. And it addresses the public infrastructure of the city rather than the private and informal infrastructure, generators, boreholes, self-built drains, on which deficit cities actually run. Each limit is a direction for further work.

5. CONCLUSION AND RECOMMENDATION

The digital twin was built to manage the infrastructure of cities that have it. It detects deterioration, predicts failure and schedules maintenance for sensed assets, and it does so well. African cities under climate stress have a different problem: the infrastructure they need has not been built, the hazard is rising and the populations most exposed are those the sensors do not reach. This

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paper has decomposed infrastructure management into maintenance, investment prioritisation and response, shown that the twin is strongest where the deficit city's need is weakest, and proposed a framework that reorients predictive modelling toward prioritisation and hazard planning, adopts a hybrid data strategy, places the model in the budgeting function with a human in the loop, and makes distributional outcomes explicit. It has derived propositions that make the framework testable and has examined, through Lagos, the risk that an unreoriented twin would make the resilient more resilient and leave the exposed where they are.

A predictive model is only as valuable as the decision it improves. In the infrastructure-deficit city the decision that matters is not how to maintain what exists but what to build, for whom, before the next flood. A digital twin that answers that question would be a different instrument from the one now on offer, less a replica of the city than an honest estimate of its hazards and its needs, and it would be the first predictive infrastructure built for the cities that need it most.

6. CONTRIBUTION TO EXISTING KNOWLEDGE

The paper contributes a decomposition of infrastructure management into the maintenance of existing assets, the prioritisation of new investment and the response to acute events, and shows that digital twins are strongest where the infrastructure-deficit city's need is weakest and weakest where it is most urgent.

It further contributes a framework that reorients predictive modelling toward investment prioritisation and hazard planning, adopts a hybrid data strategy, places the model within the budgeting function and makes distributional outcomes explicit, giving governments and financiers a standard for judging whether a digital twin will improve resilience for the exposed rather than for the already served.

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