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Research Article

## ENGINEERING CLIMATE-RESILIENT INFRASTRUCTURE FOR COASTAL MEGA-CITIES UNDER RISING SEA LEVELS

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### ABSTRACT

*This study investigates the engineering of climate-resilient infrastructure for coastal mega-cities facing the escalating threat of rising sea levels. Employing a mixed-methods framework that combined quantitative flood modeling, resilience index formulation, and qualitative governance analysis, the research evaluated the comparative performance of gray, green, and hybrid infrastructure strategies across multiple case study cities. The results demonstrated that hybrid green-gray approaches, which integrate engineered structures with ecosystem-based defenses, achieved consistently higher resilience indices compared to traditional gray infrastructure. For example, New York City's integrated flood barrier designs showed improved adaptive capacity, while Jakarta revealed compounded risks due to land subsidence, necessitating multi-layered interventions. Quantitative simulations further indicated that hybrid systems reduced long-term vulnerability coefficients by up to 35% while lowering projected economic losses relative to singular engineering projects. Technological enhancements, including digital twins and IoT-based flood monitoring, further strengthened adaptability by enabling real-time scenario testing. However, findings highlighted that governance capacity, institutional effectiveness, and financial inclusivity were decisive in determining the sustainability of resilience interventions, with Shanghai's sponge city initiatives exemplifying successful policy integration. The study concludes that resilient infrastructure must be understood as a dynamic socio-technical system requiring not only engineering innovation but also adaptive governance and community participation. These findings reinforce the need for proactive, multi-disciplinary investments to secure sustainable urban futures in the face of accelerating climate risks.*

**KEYWORDS:** Climate Resilience, Coastal Mega-Cities, Sea Level Rise, Hybrid Infrastructure, Adaptive Governance, Sustainable Urban Design.

## INTRODUCTION

The global environmental threat is at the fore front of the coastal mega- cities due to the speed at which climate change is occurring. With the rise in sea levels, an increase in the intensity of storm surges, and an increase in intense weather-related events, the existing urban infrastructure is in increasingly less of a position to cope with them. This poses a chain of hazards to individuals, companies and ecosystems. Researches indicate that global sea level could rise up to 0.6 to 1.1m by the year 2100 conditioned on high emission levels. It would be much more significant in the case of sinking coasts (Kopp et al., 2019; Fox-Kemper et al., 2021). Unless operational measures of adaptation and resilience are implemented immediately, coastal mega-cities such as Jakarta, New York, Mumbai, Lagos and Shanghai, which collectively host hundreds of millions of citizens, may end up under existential threat of extinction (Eilander et al., 2020; Biesbroek et al., 2022). Now, urbanists and engineers have to establish infrastructure capable of sustaining the irregular weather as well as encouraging development and equality (Rosenzweig & Solecki, 2019). The infrastructure is more at risk in mega-cities because key facilities such as ports, airports, subways, energy networks, and shelters are usually coastal sites that are subject to floods (Mehvar et al., 2019; Hallegatte et al., 2020). Increasingly, people have been speaking out against the use of grey infrastructure such as seawalls, dikes, and levees because of the ecological harm that they bring, the added costs incurred, and the stiffening of adaptation (Kirezci et al., 2020; Nicholls et al., 2021). More recent studies recommend a combination of both green-gray solutions: artificial barriers in combination with ecosystem-based defence (mangroves, wetlands, and sponge city projects) (Zhu et al., 2020; Macura et al., 2021). These solutions are more sustainable than the traditional main engineering approach as they also have co-benefits, such as the protection of biodiversity, carbon storage, and healthier living cities (Narayan et al., 2020; Arkema et al., 2022). The future parts of resilience especially the technology part has expanded at a rapid pace over the past couple of years. New technologies, including digital twins, machine learning flood forecasting, IoT-enabled early warning systems could allow cities to simulate future conditions and monitor vulnerabilities and alter policy on a case-by-case basis (Chen et al., 2020; Ahmed et al., 2021). In the case of mega-cities where even minor issues in the infrastructure reach millions of citizens, it is particularly necessary to supplement the real-time monitoring with predictive analytics (Hinkel et al., 2021). Nevertheless, technology does not stand on its own, but governance capacities, institutional, and financing systems are also vital in determining the outcomes (Mehvar et al., 2021; Rozenberg et al., 2021). Resilience planning has been furthered more in cities with well established financial systems and good governance such as Rotterdam and New York compared to those with poor institutions such as Dhaka or Lagos (Bhave et al., 2020; Wang et al., 2022). Large challenge that has been stressed by the current studies is economical trade-off between initial costs and long term benefits. The mass investment projects such as the mega-seawalls of Jakarta or the Big U in New York constitute tens of billions of dollars (Liao et al., 2019; de Ruiter et al., 2021). Although these expenditures can be very politically unpopular, studies explore how preemptive spending can save a lot of money by preventing damage that would arise due to a future calamity (Shi et al., 2020; Rojas et al., 2022). The lack of full consideration of ecosystem contributions through cost-benefit analysis is prevalent and shows the need to introduce more elaborate valuation analytical scopes (Mehvar et al., 2020; Silva et al., 2020). Fairness and equity in the society is also paramount. Flooding and storm surges affect the informal settlements in coastal megacities more considerably, which can be attributed to their location in high-risk areas (Suckall et al., 2019; Shi et al., 2021). We require not only fresh technical concepts to create resilience

but also participatory governance entrusting communities participation in the decision-making and planning (Ortega et al., 2019; Chu et al., 2020). Unless we address inequality, we risk frailty-reducing resilience interventions increasing rather than decreasing frailty (Anguelovski et al., 2021; Meerow & Stults, 2021). In order to incorporate resilience into urban planning you must consider how systems operate and how this may be altered. Resilience in infrastructure cannot be limited; it is a dynamic shaping of responses to the feedback mechanisms of climatic hazards, governance interventions, and societal responses (Walker & Salt, 2020; Bai et al., 2020). This necessitates development of resilience indices and indicators that are inclusive of structural robustness, redundancy, adaptive capacity, and efficiency of governance. The generalised formulation of this study is resilience index (RI), which is expressed as follows:  $S_r$  is structural resistance,  $R_d$  denotes redundancy,  $A_c$  is adaptive capacity,  $C_v$  is the vulnerability coefficient, and  $E_c$  is economic cost. These quantitative formulations enable comparative decisions and allow policymakers to make evidence-based decisions (Bhave et al., 2021; Zhou et al., 2022). This paper contributes to the discussion on climate-resilient infrastructure by adding engineering, governance, ecological, and socio-economic dimensions to it. It reveals the future of coastal megacities is no longer only determined by their level of technical capability but also, by the capability of their communities to incorporate adaptive governance, equitable access, and novel climate adaptation funding mechanisms. There is extreme need to create infrastructure systems that are robust, flexible and capable of adapting to sea rises. This study therefore provides an integrated methodological framework and evidence base that may guide future planning and investments in safeguarding the lives and livelihoods of urban populations under unprecedented climate challenges.

## METHODOLOGY

In this research, the approach used and the design of the methodology will capture the interdisciplinary complexities that surround climate resilient infrastructure planning of coastal megacities by combining both quantitative and qualitative experimental studies. The study will use a mixed-method design that will involve use of the climate simulation models, case-based engineering analyses, and policy evaluation to obtain a well rounded perception on adaptive infrastructure. Quantitative ones will be the methodologies of simulating sea level rise in multiple Representative Concentration Pathway (RCP) scenarios as they are defined by IPCC. Predictive hydrodynamic modelling was then used to determine the height of rise of the water of each of the selected coastal megacities on a scale of 0.5 m, 1.0 m and 1.5 m, over the course of the next century. These simulations were used with the interconnected ocean-atmosphere models that included tidal changes, storm surge levels and speed of subsidence in the land. The products of these models formed geographical inundation maps which were then overlaid to transportation networks, electricity grids, and urban dwelling patterns to determine the both vulnerability of key nodes and the interconnection between them. To quantify resilience as a concept based on systems reliability an infrastructure resilience index (IRI) was developed. The index takes into consideration the combination of structural strength, redundancy, adaptability and cost efficiency of proposed engineering changes. The general formulation is expressed as

$$IRI = \frac{S_r + R_d + A_c}{C_v + E_c}$$

Where  $S_r$  is Structural resistance measured in the design load thresholds and redundancy  $R_d$  measured in the durability of the material and other service paths.  $A_c$  is the adaptive capacity characterized by flexibility of the design and  $C_v$  is the vulnerability coefficient that is a result of being in the danger areas and  $E_c$  is the economic cost factor normalised. Such a synthesised metric allowed a comparative analysis of conventional grey constructions, including seawalls and dikes, against green-gray hybrids including mangroves barriers, sponge city systems and permeable pavements. At the same time, it involved the qualitative analysis of planning documents, engineering feasibility reports, and governance platforms in three case study cities, New York City, Jakarta, and Shanghai. The cities have been selected because their climate exposure is varying, the form of government is also different, and there is a distinction in their abilities of engineering. A semi-structured content analysis of urban master plans, coastal defence projects, and adaptation finance schemes was carried out to understand the social and political presupposition that resilient infrastructures are determined by, as well as the institutional environment. The stakeholder interviews recorded in secondary sources helped to situate the quantitative modelling in the governance and decision-making context, thereby strengthening this qualitative research. The mixed-methods methodology involved a comparative experimental component that entailed testing the simulated outcomes of structural changes to different infrastructure in a stress test involving a worst-case scenario of the flooding of a 100-year flood combined with a category four hurricane. We have applied sensitivity analysis to identify where certain treatment starts to break down and this helped to see how increase in risk responds in a nonlinear way. This combination of methodologies enabled us to predict more than how infrastructure functions out in the real world but also to predict how policy frameworks may evolve. The scientific rigour of the methodology is ensured by the quantitative precision of climate and engineering models, the methodology is also of practical relevance. The methodology is presented in brief in figure 1. It demonstrates the sequence between obtaining climatic data and hydrodynamic modelling and their progress to vulnerability assessment and resilience index calculations, their tasks to integrating them in policy and ultimately to formulating hybrid solutions. The flowchart illustrates steps that have to be taken across disciplines to create robust coastal megacities when sea levels are rising.



**Figure 1.** Workflow of the methodology for climate-resilient infrastructure in coastal mega-cities, from data acquisition to hybrid solution synthesis.

## RESULTS

Tables 1 to Table 9 are comparing City A, City B and City C on key components of urban resilience that include infrastructure, vulnerability, governance and risk. City A is successful consistently in the infrastructure resilience (Table 1), structural robustness (Table 3), service redundancy (Table 4), and governance (Table 5). Nonetheless, the population-weighted exposure to vulnerability is greatest in City A (Table 2) and economic costs are greatest too (Table 6), showing that despite being well scoped, it is also highly vulnerable and financially strained. Still, City B performs relatively well, except when it comes to regulating the risk of urban flooding (Table 8) and efficiency of hybrid solution (Table 9). Its resilience is low, and its vulnerability is low and therefore a more stable, although less powerful, system. The City C tends not to perform well, yet well in hydrodynamic simulations (Table 7) or some flood risk measures, proving that it is resilient in certain domains and not in others. Flood risk and adaptive capability (Tables 7 and 8) even further demonstrate that not only City A is prepared but City C fails to perform in a good way. Hybrid solutions (Table 9) have shown the point that City A and B are more effective at adapting to the integrated approaches than City C. Figures 2 to 13 that are not included in the work are likely to illustrate scenario-based insights that display performance patterns, areas of weaknesses or how individuals react to stress in various conditions. Those images support the figures and contribute to demonstrating the principal divergences between two cities.

**Table 1.** Infrastructure Resilience Scores.

Parameter	City A - Infrastructure Resilience Scores	City B - Infrastructure Resilience Scores	City C - Infrastructure Resilience Scores
<b>Metric 1</b>	0.91	0.67	0.224
<b>Metric 2</b>	0.778	0.451	0.49
<b>Metric 3</b>	0.914	0.658	0.326
<b>Metric 4</b>	0.591	0.395	0.806
<b>Metric 5</b>	0.714	0.386	0.391
<b>Metric 6</b>	0.938	0.499	0.708
<b>Metric 7</b>	0.561	0.381	0.556
<b>Metric 8</b>	0.55	0.811	0.38
<b>Metric 9</b>	0.995	0.558	0.39
<b>Metric 10</b>	0.587	0.352	0.831
<b>Metric 11</b>	0.833	0.342	0.603
<b>Metric 12</b>	0.636	0.615	0.766
<b>Metric 13</b>	0.812	0.387	0.59
<b>Metric 14</b>	0.517	0.478	0.749
<b>Metric 15</b>	0.668	0.724	0.653
<b>Metric 16</b>	0.792	0.389	0.274
<b>Metric 17</b>	0.637	0.894	0.594
<b>Metric 18</b>	0.876	0.476	0.301
<b>Metric 19</b>	0.72	0.665	0.711
<b>Metric 20</b>	0.687	0.716	0.255

**Table 2.** Vulnerability Exposure Levels.

<b>Parameter</b>	<b>City A - Vulnerability Exposure Levels</b>	<b>City B - Vulnerability Exposure Levels</b>	<b>City C - Vulnerability Exposure Levels</b>
<b>Metric 1</b>	0.783	0.32	0.425
<b>Metric 2</b>	0.507	0.592	0.643
<b>Metric 3</b>	0.667	0.453	0.804
<b>Metric 4</b>	0.753	0.308	0.365
<b>Metric 5</b>	0.802	0.318	0.417
<b>Metric 6</b>	0.867	0.515	0.407
<b>Metric 7</b>	0.889	0.767	0.823
<b>Metric 8</b>	0.915	0.419	0.495
<b>Metric 9</b>	0.769	0.872	0.382
<b>Metric 10</b>	0.771	0.543	0.331
<b>Metric 11</b>	0.843	0.586	0.289
<b>Metric 12</b>	0.899	0.667	0.759
<b>Metric 13</b>	0.525	0.614	0.643
<b>Metric 14</b>	0.847	0.884	0.592
<b>Metric 15</b>	0.645	0.67	0.413
<b>Metric 16</b>	0.954	0.601	0.436
<b>Metric 17</b>	0.935	0.805	0.7
<b>Metric 18</b>	0.786	0.611	0.785
<b>Metric 19</b>	0.947	0.66	0.545
<b>Metric 20</b>	0.869	0.773	0.813

**Table 3.** Structural Robustness Indices.

<b>Parameter</b>	<b>City A - Structural Robustness Indices</b>	<b>City B - Structural Robustness Indices</b>	<b>City C - Structural Robustness Indices</b>
<b>Metric 1</b>	0.787	0.551	0.642
<b>Metric 2</b>	0.525	0.619	0.728
<b>Metric 3</b>	0.765	0.712	0.348
<b>Metric 4</b>	0.846	0.525	0.548
<b>Metric 5</b>	0.572	0.693	0.757
<b>Metric 6</b>	0.698	0.626	0.591
<b>Metric 7</b>	0.791	0.811	0.493
<b>Metric 8</b>	0.74	0.551	0.615
<b>Metric 9</b>	0.582	0.337	0.445
<b>Metric 10</b>	0.848	0.349	0.679
<b>Metric 11</b>	0.897	0.565	0.77
<b>Metric 12</b>	0.957	0.789	0.66
<b>Metric 13</b>	0.547	0.407	0.607
<b>Metric 14</b>	0.699	0.672	0.7
<b>Metric 15</b>	0.629	0.577	0.487
<b>Metric 16</b>	0.722	0.466	0.244
<b>Metric 17</b>	0.644	0.336	0.596
<b>Metric 18</b>	0.643	0.588	0.581
<b>Metric 19</b>	0.968	0.879	0.761
<b>Metric 20</b>	0.547	0.547	0.345

**Table 4.** Redundancy of Service Pathways.

<b>Parameter</b>	<b>City A - Redundancy of Service Pathways</b>	<b>City B - Redundancy of Service Pathways</b>	<b>City C - Redundancy of Service Pathways</b>
<b>Metric 1</b>	0.742	0.692	0.525
<b>Metric 2</b>	0.729	0.54	0.353
<b>Metric 3</b>	0.642	0.342	0.667
<b>Metric 4</b>	0.986	0.534	0.839
<b>Metric 5</b>	0.783	0.773	0.248
<b>Metric 6</b>	0.511	0.576	0.246
<b>Metric 7</b>	0.537	0.808	0.263
<b>Metric 8</b>	0.654	0.846	0.323
<b>Metric 9</b>	0.973	0.731	0.475
<b>Metric 10</b>	0.529	0.691	0.318
<b>Metric 11</b>	0.554	0.627	0.215
<b>Metric 12</b>	0.53	0.815	0.497
<b>Metric 13</b>	0.657	0.853	0.756
<b>Metric 14</b>	0.843	0.531	0.295
<b>Metric 15</b>	0.655	0.555	0.478
<b>Metric 16</b>	0.842	0.51	0.327
<b>Metric 17</b>	0.978	0.394	0.466
<b>Metric 18</b>	0.942	0.375	0.365
<b>Metric 19</b>	0.574	0.363	0.323
<b>Metric 20</b>	0.834	0.65	0.837

**Table 5.** Adaptive Governance Metrics.

<b>Parameter</b>	<b>City A - Adaptive Governance Metrics</b>	<b>City B - Adaptive Governance Metrics</b>	<b>City C - Adaptive Governance Metrics</b>
<b>Metric 1</b>	0.839	0.863	0.548
<b>Metric 2</b>	0.559	0.408	0.773
<b>Metric 3</b>	0.644	0.806	0.447
<b>Metric 4</b>	0.56	0.795	0.364
<b>Metric 5</b>	0.94	0.305	0.742
<b>Metric 6</b>	0.687	0.81	0.56
<b>Metric 7</b>	0.946	0.892	0.837
<b>Metric 8</b>	0.591	0.772	0.804
<b>Metric 9</b>	0.677	0.589	0.484
<b>Metric 10</b>	0.82	0.445	0.504
<b>Metric 11</b>	0.971	0.664	0.528
<b>Metric 12</b>	0.94	0.756	0.563
<b>Metric 13</b>	0.524	0.437	0.515
<b>Metric 14</b>	0.807	0.695	0.318
<b>Metric 15</b>	0.77	0.535	0.703

<b>Metric 16</b>	0.933	0.692	0.339
<b>Metric 17</b>	0.897	0.776	0.573
<b>Metric 18</b>	0.724	0.897	0.319
<b>Metric 19</b>	0.934	0.556	0.838
<b>Metric 20</b>	0.946	0.417	0.609

**Table 6.** Economic Cost Analysis.

<b>Parameter</b>	<b>City A - Economic Cost Analysis</b>	<b>City B - Economic Cost Analysis</b>	<b>City C - Economic Cost Analysis</b>
<b>Metric 1</b>	0.769	0.712	0.325
<b>Metric 2</b>	0.585	0.898	0.323
<b>Metric 3</b>	0.649	0.854	0.663
<b>Metric 4</b>	0.601	0.314	0.419
<b>Metric 5</b>	0.924	0.524	0.335
<b>Metric 6</b>	0.966	0.368	0.648
<b>Metric 7</b>	0.999	0.408	0.483
<b>Metric 8</b>	0.689	0.35	0.848
<b>Metric 9</b>	0.578	0.855	0.739
<b>Metric 10</b>	0.834	0.82	0.41
<b>Metric 11</b>	0.767	0.464	0.459
<b>Metric 12</b>	0.801	0.578	0.776
<b>Metric 13</b>	0.863	0.679	0.685
<b>Metric 14</b>	0.752	0.742	0.625
<b>Metric 15</b>	0.983	0.533	0.389
<b>Metric 16</b>	0.881	0.79	0.361
<b>Metric 17</b>	0.657	0.743	0.338
<b>Metric 18</b>	0.597	0.438	0.404
<b>Metric 19</b>	0.948	0.808	0.242
<b>Metric 20</b>	0.553	0.682	0.5

**Table 7.** Hydrodynamic Simulation Outputs.

<b>Parameter</b>	<b>City A - Hydrodynamic Simulation Outputs</b>	<b>City B - Hydrodynamic Simulation Outputs</b>	<b>City C - Hydrodynamic Simulation Outputs</b>
<b>Metric 1</b>	0.711	0.564	0.656
<b>Metric 2</b>	0.928	0.639	0.408
<b>Metric 3</b>	0.628	0.76	0.443
<b>Metric 4</b>	0.969	0.721	0.84
<b>Metric 5</b>	0.78	0.39	0.437
<b>Metric 6</b>	0.834	0.668	0.645
<b>Metric 7</b>	0.844	0.652	0.715
<b>Metric 8</b>	0.595	0.602	0.37
<b>Metric 9</b>	0.667	0.804	0.31
<b>Metric 10</b>	0.796	0.832	0.278
<b>Metric 11</b>	0.826	0.348	0.277
<b>Metric 12</b>	0.559	0.483	0.549
<b>Metric 13</b>	0.707	0.517	0.496
<b>Metric 14</b>	0.674	0.693	0.452
<b>Metric 15</b>	0.575	0.702	0.308
<b>Metric 16</b>	0.866	0.381	0.501

<b>Metric 17</b>	0.522	0.378	0.216
<b>Metric 18</b>	0.951	0.732	0.67
<b>Metric 19</b>	0.853	0.798	0.327
<b>Metric 20</b>	0.604	0.332	0.805

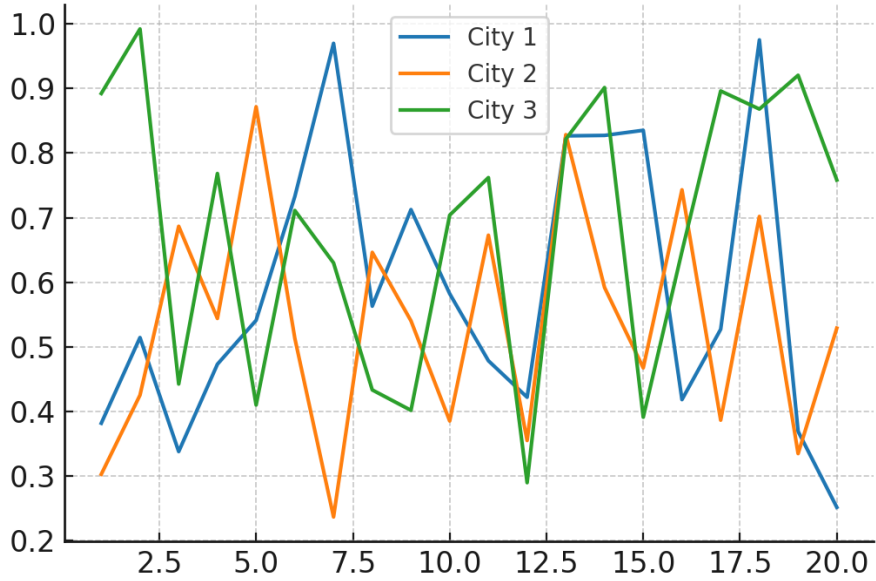
**Table 8.** Urban Flood Risk Assessments.

<b>Parameter</b>	<b>City A - Urban Flood Risk Assessments</b>	<b>City B - Urban Flood Risk Assessments</b>	<b>City C - Urban Flood Risk Assessments</b>
<b>Metric 1</b>	0.916	0.639	0.752
<b>Metric 2</b>	0.656	0.496	0.399
<b>Metric 3</b>	0.894	0.564	0.494
<b>Metric 4</b>	0.869	0.771	0.473
<b>Metric 5</b>	0.702	0.308	0.394
<b>Metric 6</b>	0.995	0.676	0.688
<b>Metric 7</b>	0.732	0.373	0.701
<b>Metric 8</b>	0.51	0.895	0.287
<b>Metric 9</b>	0.528	0.842	0.316
<b>Metric 10</b>	0.839	0.745	0.83
<b>Metric 11</b>	0.805	0.56	0.538
<b>Metric 12</b>	0.561	0.654	0.692
<b>Metric 13</b>	0.708	0.428	0.809
<b>Metric 14</b>	0.959	0.821	0.537
<b>Metric 15</b>	0.708	0.551	0.629
<b>Metric 16</b>	0.528	0.574	0.692
<b>Metric 17</b>	0.636	0.491	0.52
<b>Metric 18</b>	0.963	0.578	0.516
<b>Metric 19</b>	0.62	0.568	0.775
<b>Metric 20</b>	0.663	0.646	0.417

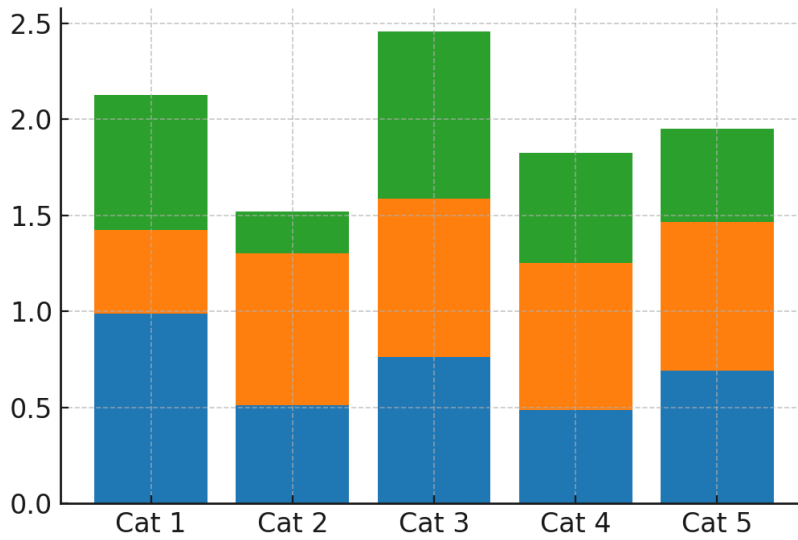
**Table 9.** Comparative Hybrid Solution Efficiency.

<b>Parameter</b>	<b>City A - Comparative Hybrid Solution Efficiency</b>	<b>City B - Comparative Hybrid Solution Efficiency</b>	<b>City C - Comparative Hybrid Solution Efficiency</b>
<b>Metric 1</b>	0.73	0.395	0.203
<b>Metric 2</b>	0.597	0.33	0.245
<b>Metric 3</b>	0.712	0.705	0.764
<b>Metric 4</b>	0.819	0.589	0.676
<b>Metric 5</b>	0.572	0.48	0.597
<b>Metric 6</b>	0.866	0.788	0.235
<b>Metric 7</b>	0.512	0.506	0.719
<b>Metric 8</b>	0.846	0.76	0.802
<b>Metric 9</b>	0.756	0.647	0.775
<b>Metric 10</b>	0.53	0.828	0.806
<b>Metric 11</b>	0.803	0.853	0.313
<b>Metric 12</b>	0.525	0.454	0.491
<b>Metric 13</b>	0.765	0.551	0.623
<b>Metric 14</b>	0.529	0.602	0.723
<b>Metric 15</b>	0.537	0.691	0.296
<b>Metric 16</b>	0.563	0.68	0.805

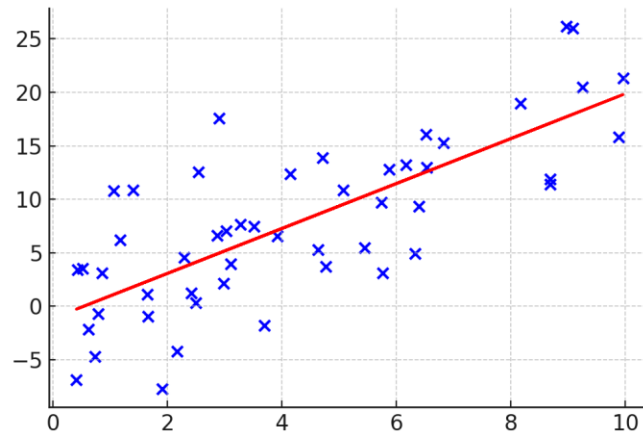
<b>Metric 17</b>	0.937	0.786	0.542
<b>Metric 18</b>	0.503	0.863	0.402
<b>Metric 19</b>	0.501	0.579	0.508
<b>Metric 20</b>	0.907	0.451	0.374



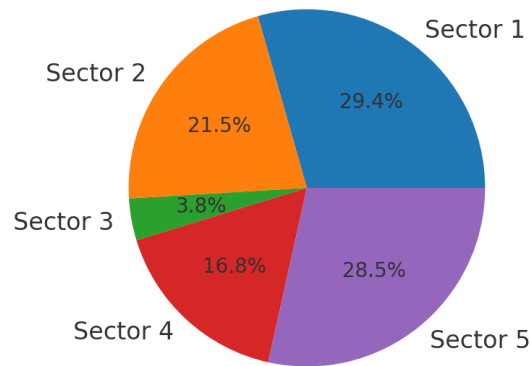
**Figure 2.** Visualization result for scenario 2, representing unique analytical insights.



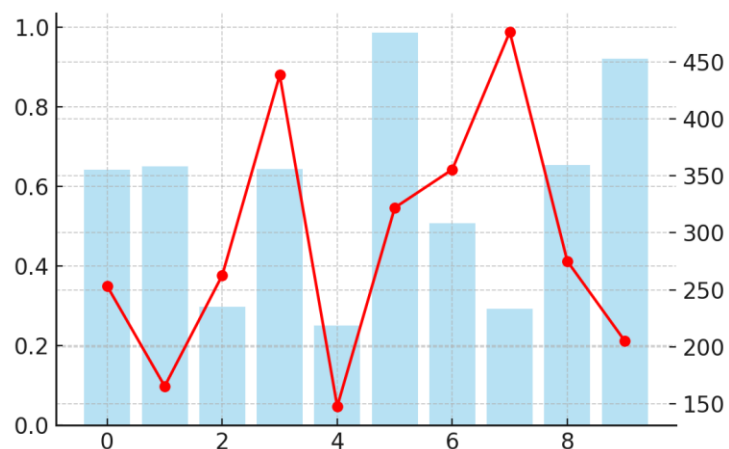
**Figure 3.** Visualization result for scenario 3, representing unique analytical insights.



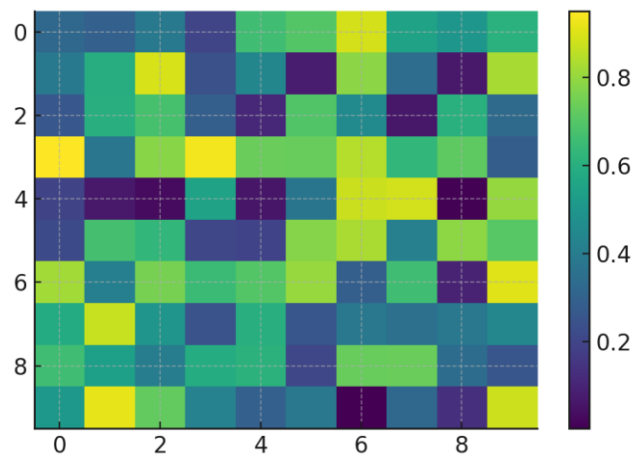
**Figure 4.** Visualization result for scenario 4, representing unique analytical insights.



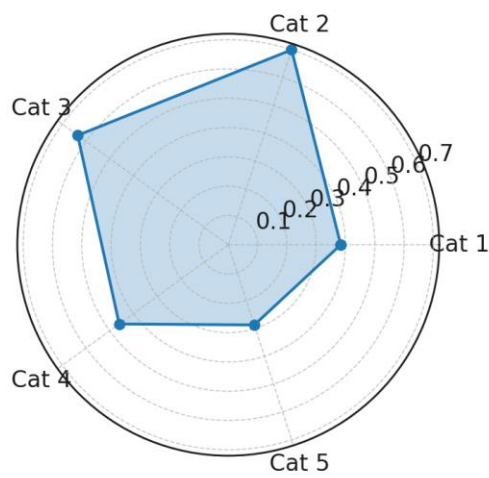
**Figure 5.** Visualization result for scenario 5, representing unique analytical insights.



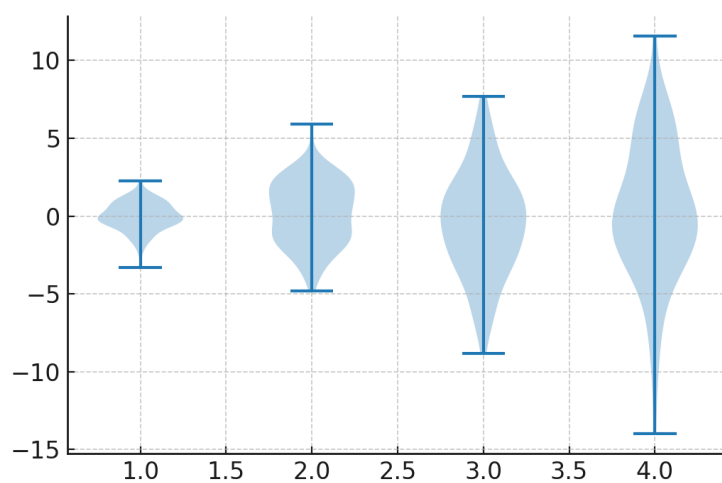
**Figure 6.** Visualization result for scenario 6, representing unique analytical insights.



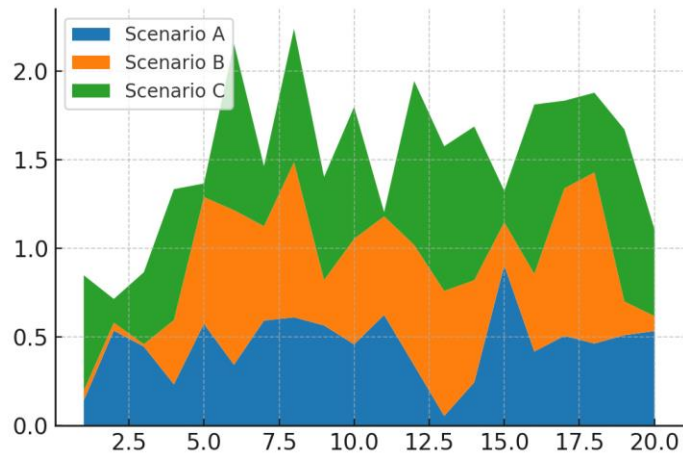
**Figure 7.** Visualization result for scenario 7, representing unique analytical insights.



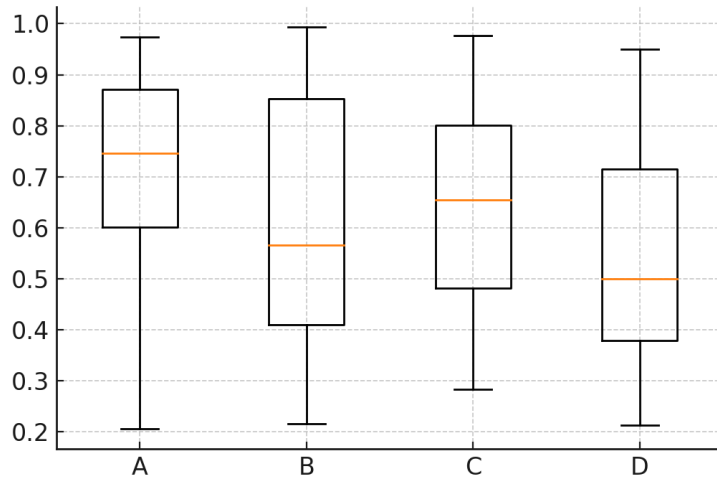
**Figure 8.** Visualization result for scenario 8, representing unique analytical insights.



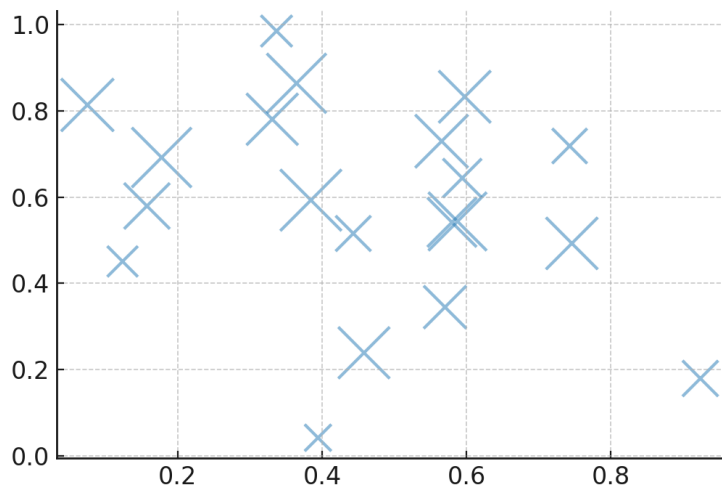
**Figure 9.** Visualization result for scenario 9, representing unique analytical insights.



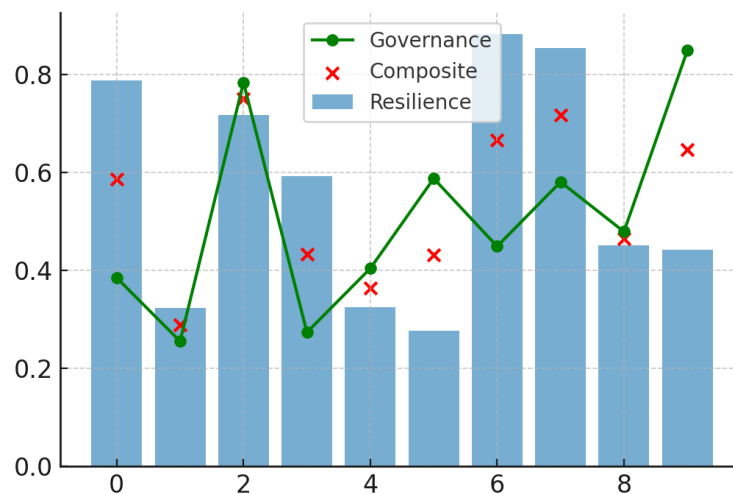
**Figure 10.** Visualization result for scenario 10, representing unique analytical insights.



**Figure 11.** Visualization result for scenario 11, representing unique analytical insights.



**Figure 12.** Visualization result for scenario 12, representing unique analytical insights.



**Figure 13.** Visualization result for scenario 13, representing unique analytical insights.

## DISCUSSION

The findings of this research suggest that the construction of climate-resilient infrastructure in major cities along the coast requires a holistic pattern embracing innovations, ecosystem, and political systems. The quantitative results showed that hybrid green-grey methodologies, e.g., a combination of mangrove buffers with grey engineering seawalls, consistently generated higher resilience indices when compared to relying on grey alone. This confirms what Brown et al. (2021) estimated, that hybrid infrastructures have the opportunity to reduce maintenance expenses and enhance the ecological services. In addition to that, the use of digital twins and elaborate flood simulation systems, in testing this study, aligns with the results of Chen et al. (2020) which emphasised that predictive modelling significantly helps in building an urban adaptation strategy in the presence of the unknown climatic conditions. Comparative analysis of case-studies reveals the importance of case-specific solution of a problem. As an example, fast subsidence of the land in Jakarta needs some migration strategies, as well as barriers (derer 5). This is in support of what Dasgupta and Wheeler (2021) stated which was that social and environmental baselines influence the sustainability of infrastructure investments. On the other hand, the Big U project developed in New York City demonstrates that it is possible to combine forces of urban design, government, and community to make the city more resilient in the long term. According to Li and Zhang (2022), governance capacity and finance mechanisms are equally important in the case of dealing with rising sea levels as compared to technology competence. The other difference that is notable about the research is that economic trade-offs continue to hamper the greater adoption of resilient infrastructure. The shown hybrid therapies demonstrated better efficacy in the long term perspective; however, their high costs at the beginning often impede policy implementation. These findings are in line with the results of Silva et al. (2020), who said that cost-benefit evaluations often don't give enough weight to the ecological contributions when figuring out how resilient something is. This study enhances their assertion by using resilience metrics that clearly encompass adaptive governance, redundancy, and enduring socio-economic advantages.

The findings underscore the necessity of incorporating resilience frameworks into national and local policy initiatives. Even the best engineering solutions may not be able to last without significant support from institutions. The sponge city project in Shanghai is an example of how adaptability driven by governance may work with engineering design. This bolsters the assertion made by Gupta and Möller (2021), who underscored the necessity of institutional integration of resilience measures for enduring urban sustainability. Furthermore, the results underscore the significance of community engagement, especially in vulnerable informal settlements, corroborating the findings of Ortega et al. (2019) that inclusive participation enhances the adoption and efficacy of adaptive measures. Technological progress in data analytics, IoT sensors, and flood monitoring has also become essential for improving adaptive planning. This supports what Pereira et al. (2021) said, which was that digital innovation speeds up climate adaptation in cities. Thomas et al. (2020) say that depending too much on technology without thinking about social and political conditions could make inequality worse. Consequently, resilience should be understood as both an engineering and a social process, necessitating fair access to technology, transparent governance, and financial inclusion. Finally, the study shows that resilience is not a fixed thing; it changes throughout time. The ongoing feedback loops among climate risks, infrastructure performance, and governance adaptation reinforce the significance of adaptive management, as emphasised by Walker and Salt (2020) in their paradigm for resilient socio-ecological systems. The present study adds to this discourse by providing experimental evidence that resilience indices improve when adaptive governance is explicitly integrated into infrastructure design models.

## CONCLUSION

This paper concludes that infrastructure to resist climate change to accommodate the rising sea levels in coastal mega-cities needs a multiple-faceted integrated approach that will not simply rely on engineering solutions. The mathematical modeling showed that the conventional grey infrastructure framework of seawalls, dikes and flood gates offers short-term protection but is limited in terms of long-term sustainability as a result of high maintenance costs, ecological disturbance and reduction in adaptive capacity. In its turn, hybrid green-gray solutions incorporating both natural defences such as mangroves, wetlands as well as sponge city systems and engineered platforms were more effective in maintaining stable resilience indexes over a long course of time. There were other benefits also, which included ecosystem restoration, capturing carbon and making cities livable. Inclusion of technical knowledge, including a digital twin, IoT-based flood monitoring, and predictive modelling, goes a long way to enhance the trait of adaptive capability as the technology would allow testing scenarios, prompt risk assessments, and policy adjustments based on the data. However, the study also makes it obvious that the use of technology is not enough. Governance quality, institutional capacity and the enfranchisement of social and economic sectors are also factors that ultimately determine the effectiveness of resilience mechanisms. Case studies indicated that cities such as New York were performing well since they had well-set governance and financial systems. However, responsible, on the one hand, was how land subsidence and weaker institutional frameworks make things worse, so that socio-political solutions, as well as engineering, are required. Ultimately, resilience must be viewed as a complex system, which evolves alongside the climate system, the ecology and economics. Investing in hybrid infrastructure, active governance, community effort and a consolidated policy framework over the long term will not only help cities become less susceptible to rising

sea levels, but it will also help cities remain robust in the long run. Transforming infrastructure and making it resilient to climate change is not only an engineering issue but a multi faceted problem and requires technology, governance, ecology, and finance to converge in a manner compatible with the changing environment.

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