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Functional Sufficiency of Coastal Blue–Green Adaptation: Hydro-Institutional Evidence from Chennai and Kochi, India

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Abstract

Coastal adaptation requires a direct contrast between the level of local climate pressure and the utility provided by the functions associated with the blue-green action. In this case, we focus on Chennai and Kochi, Indian coastal cities facing climate pressure from exposure to sea-level rise, heavy rain, warming, drainage challenges, and land use. These two cities experience all five pressures without generating similar climate adaptation needs. Hydro-Institutional Adaptation Partitioning (HIAP) is used to translate the values of 2080 climate projections and planning actions into four pairs of dimensions that include: thermal pressure, sea-level pressure, rainfall-regime pressure, and extreme-event pressure. The planning cover was operationalized based on national policy and planning program support, climate planning, wetland/biodiversity projects, and participation in canal governance. It is observed that the two cities had a consistent number of action classes of four, yet different adaptation needs. Chennai has the larger sea-level coefficient than that of Kochi and maintains small uncovered pressure in both thermal and sea-level dimensions. On the other hand, Kochi has the highest overall climate pressure due to high levels of warming and decline in mean rainfall. The latter also maintains the larger uncovered pressure related to thermal moderation and rainfall retention capacity. Sensitivity tests revealed that the uncovered climate pressure in Kochi increased with respect to heat-dryness weighting, whereas Chennai stayed responsive to sea-level drainages and heat sensitive open spaces.

Keywords: blue–green infrastructure; climate adaptation; coastal planning; Chennai; Kochi; nature-based solutions; urban flooding; institutional capacity

1. Introduction

Coastal urban adaptation used to be concerned solely with flood mitigation. Sea-level rise alters coastal topography, tidal backwater dynamics, and gravity flow. Extreme rainfall imposes short-term stress on stormwater management systems, tanks, canals, wetlands, and low lying roadways. Warming amplifies the need for shade, evapotranspiration, access to open space, and water-responsive landscape architecture. Regime change adds further complexity since some cities will need to address not only rainfall intensity but also rainfall deficit. But these phenomena are not imposed on an empty surface. Land-use conversion, housing inequalities, informality, institutional fragmentation, and degradation of wetlands, tanks, canals, marshes, and green spaces lie underneath the pressure.

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Multi-functional blue-green infrastructure has emerged as a key response to these compounded phenomena. It includes rivers, canals, tanks, wetlands, backwaters, marshlands, ponds, lakes, parks, green corridors, floodable open spaces, and designed landscapes which can provide multiple ecosystem services. Research has shifted from treating this kind of infrastructure as an amenity toward recognizing its contribution to adaptation in terms of flood mitigation, thermal cooling, ground water replenishment, biodiversity, carbon storage, air quality improvement, recreation, and public health [5, 13, 15, 16]. Similarly, the nature-based solutions approach emphasizes that urban adaptation must rest on the foundation of demonstrable efficacy, multiple co-benefits, maintenance, and institutional translation [3, 13, 41].

There is a persistent gap in the application of this knowledge: blue-green planning tends to measure progress in terms of visible institutional presence. A city might have a climate action plan, a wetland management plan, canals upgrades, and national policy support, but none of these indicate that the portfolio is responsive to the dominant climate pressures. The issue is that urban adaptation differs from one city to another. While one city may benefit from additional measures to deal with the effect of sea-level rise on the city drainage, another may need water retention capacity during dry periods. The existence of action plans alone creates an illusion of adaptation success until the functional distribution of action is compared to the functional distribution of pressure.

The present analysis applies a comparative approach to a pair of Indian coastal cities – Chennai and Kochi. Both have experienced significant floods and are well known for their urban wetlands and canals. The two cities have also taken steps toward developing blue-green infrastructure and are exposed to similar pressure from sea-level rise, extreme rainfall, warming, urbanization, and drainage problems. However, they differ in terms of relative contributions to their urban climate pressures. Chennai has a significantly higher sea-level projection while Kochi experiences much stronger warming and rainfall deficiency. At the same time, both cities use different institutional mechanisms for dealing with climate problems: Resilient Chennai Strategy, Pallikaranai Marshland, Buckingham Canal; and Kerala State Action Plan on Climate Change, Local Biodiversity Strategy and Action Plan, Mullassery Canal.

The aim of this analysis is to develop an efficient way to translate city projection values and actions into an understanding of institutional fit in climate-adaptation planning. This is achieved through Hydro-Institutional Adaptation Partitioning that converts projection data into standardized climate pressure, maps institutional cover onto functional adaptation needs, and measures uncovered pressure per climate dimension. The purpose of the methodology is not to replace complex hydraulic simulations, field research, or detailed neighborhood vulnerability assessments but rather help planners decide what and where further investigation is needed in case of uneven but real adaptation planning activity.

This is a practical paper that contributes to knowledge by demonstrating how limited empirical inputs can produce useful information about institutional and functional pressure cover without making unfounded assumptions. The content of this analysis shows that Chennai and Kochi cities share comparable institutional breadth but distinct adaptation priorities: the former needs better coordination of coastal exposure, marshland storage, canal conveyance, and cooling open space while the latter requires seasonal retention capacity, protection of marshlands from desiccation, provision of shade, and productive water landscape.

2. Scientific background and planning rationale

2.1. Multifunctional blue–green infrastructure

Early studies of urban green infrastructure highlighted their multifunctionality: when planned together, the same land system may perform different functions at the same time and thus provide multiple ecosystem services [15, 16, 36]. This idea is particularly relevant in the context of coastal cities because their assets usually serve a variety of purposes: wetlands can store excess water, recharge groundwater, act as a buffer against saline intrusion, support biodiversity, and cool down the surrounding environment. Canals can help in transporting water from one place to another while connecting communities to waterfront open space. A park can be used for leisure activities, as well as provide space for flood storage and cooling in summer days. What is unique about blue-green infrastructure is that its functions complement one another.

Urban climate studies add a scientific dimension to this concept by establishing the link between water bodies and urban warming while confirming that open green spaces can cool down cities in times of heat waves [5, 11]. Likewise, urban flood mitigation studies have proven the necessity of integrating retention and infiltration into water transportation networks [11, 38]. This information cannot be treated as justification for abolishing all types of grey infrastructure, but instead, provides insight into the fact that adaptive urban environments have to be integrated systems of drainage, green spaces, and water bodies.

Studies of nature-based solutions further expand our understanding of adaptation needs through performance and governance analysis. In order for a wetland to maintain its storage capacity, it should not be allowed to be encroached by buildings. In order for a canal to keep its conveyance capacity, there must be waste management measures in place. And in order for urban greening projects to succeed, there must be mechanisms to ensure social fairness of decision-making process. Thus, adaptation planning requires taking into account ecological, hydrological, land regulations, finance, community legitimacy, and maintenance aspects of each urban intervention [8, 13, 41, 47].

2.2. Compounding urban pressure and institutional fit

Climate risk is increasingly discussed in terms of its compound character [27]: high rainfall, river discharge, storm surge, high tide, drainage congestion, and sea-level rise can create situations that go beyond the contribution of any of those elements [46]. Similarly, urbanization can compound the impact of climate events since flood exposure, heat exposure, housing insecurity, inadequate sanitation facilities, and transport disruptions affect different neighborhoods to a different extent. For instance, IPCC Sixth Assessment Report highlights the importance of institutional capacity in addressing vulnerability, infrastructure conditions, and intersector coordination for urban adaptation [27].

For urban adaptation planning, the compound nature of risks translates into the need to coordinate different institutions which often do not interact with one another. While a climate action plan may identify certain vulnerabilities, a regulatory body will be responsible for enforcing zoning. A wetland agency may protect ecological land but need waste management measures to keep canal clear. While canal projects may improve canal maintenance, they also need regulatory support to avoid future encroachment by buildings. The point is that the institutional layers must overlap.

Urban resilience scholars have been warning about overgeneralization of resilience concepts and the need to apply them practically [35, 39]. When it comes to adaptation planning, this means that cities need methods of diagnosing climate risks based on actionable and transparent measures. These measures have to be straightforward yet specific to address climate risks. Hence, HIAP was designed to work in this transitional zone of planning knowledge: it is less detailed than hydrodynamic simulation but more transparent than an inventory of plans and projects.

2.3. Indian coastal cities and blue–green governance

The Indian urban landscape has changed drastically over the past decades due to fast urbanization that took place over coastal wetlands, water bodies, agricultural lands, and marshlands [2]. Such urbanization pattern has resulted in land-use alteration that reduced the drainage capacity of the land, increased runoff, and put vulnerable communities close to flood zones [2]. In turn, the experience of Indian cities shows that urbanization patterns play a crucial role in determining the outcome of climate events [22–24, 40].

The situation is even more exacerbated by urban institutional fragmentation and lack of technical resources that characterize many Indian cities [4, 31, 42]. Yet, thanks to 74th Constitutional Amendment Act of 1992 and other policies that followed, the conditions became more favorable for blue-green adaptation [1, 19, 20]. In particular, AMRUT and Smart Cities Missions helped to draw attention to water sensitive urban design, lake restoration, drainage, and green space [1, 19, 20]. However, they did not address the specific climate functions in different Indian cities.

It is easy to see how both opportunities and obstacles are reflected in the current climate-adaptation practices of Chennai and Kochi cities. Both cities have recently taken steps toward implementing multi-functional blue-green infrastructure in the context of climate adaptation. However, their climate pressures are different. A tool that simply records whether a city has a wetland project or a flood control scheme cannot reveal these differences in pressures. The following analysis seeks to do just that by comparing cities' climate pressures and adaptation action coverage within the same pressure dimensions.

3. Study cities and empirical inputs

Figure 1 presents the comparison in the visual form using paired city-view maps. As can be seen from Figure 1, Chennai is a coast–canal–marsh combination while Kochi represents a coast–backwater–canal combination.

(**a**) Chennai. (**b**) Kochi.

Figure 1. Coastal blue–green settings.

The difference in Figure 1 helps explain why the two-city comparison is not simply based on general exposure to a coastal setting. Adaptation for Chennai depends on the relationship between marshland retention, canal conveyance, and coastal release. Adaptation for Kochi depends on how a water-rich backwater system can continue to perform hydrologically and thermally even as urban development encroaches upon canals, wetlands, and low-lying areas.

3.1. Chennai: drainage challenges, marshland degradation, and heat-sensitive expansion

Chennai is located on the Bay of Bengal and has developed on a low-lying coastal landscape marked by rivers, tanks, marshlands, backwaters, and canals. Its urban agglomeration grew from 2.64 million people in 1971 to 4.68 million in 2011, with metropolitan area numbers estimated at over 9 million in recent years [7, 26]. The extent of the municipal area has expanded from 176 sq. km. to 426 sq. km. in 2011, while the built-up surface rose to 88% in 2017 as a result of a 20% increase from 1997 to 2017 [26]. Such trends involved the decline of vegetation, open spaces, wetlands, and water bodies, as well as the expansion of growth in flood-prone zones.

The blue–green structure of Chennai involves rivers such as the Buckingham Canal, the Adyar River, the Cooum River, the Pallikaranai Marshland, tanks, lakes, and storm-water conveyance systems. The Buckingham Canal, created since the nineteenth century, initially played a crucial role in providing connections between the backwaters, as well as transport and drainage services. However, with the reduction of transport needs, canal segments suffered from degradation caused by encroachment, siltation, pollution, and lack of proper management [24, 45]. The Pallikaranai Marshland is essential because storm-water from Velachery enters the marshland and then flows through Okkiyam Maduvu into the Buckingham Canal. Recent research has revealed that urbanization and growth have made Chennai flood-prone due to land conversion and loss of storage capacity [12, 28, 44].

Low-income settlements also contribute to the same hydrological problem. Such settlements tend to cluster around canals and riverbeds as affordable options, while access to such municipal facilities as drinking water supply and sewerage has been poor in some of these areas [29, 30]. The city suffers from a shortage of green spaces too: in planning literature, less than 1 sq. m of green space is mentioned per capita, which is considerably lower than the average 10-12 sq. m proposed in the debate about urban green spaces in India [21]. Thus, adaptation in Chennai cannot be reduced to canal desilting and wetland protection but will require coordination between various aspects of the blue-green environment.

3.2. Kochi: backwater landscape, canal stress, and seasonal water risks

Kochi is situated on the west coast of India between the Malabar Coast and the Vembanad Lake. The Kochi Municipal Corporation comprises an area of approximately 98 sq. km., while the urban population reaches 0.6 million in the municipality and approximately 2.5 million in the urban agglomeration in 2011 [7, 26]. Economic activities include the port industry, information technology, electronics, and associated enterprises. However, the city faces multiple environmental challenges as a result of its coastal and backwater setting that expose it to flood, erosion, sea-level rise, and drainage difficulties.

Water is essential for Kochi's urban structure: backwaters controlled by the city encompass 23.31 sq. km., while inland backwaters, canals, marshlands, and ponds occupy 7.25% of the urban surface area [25]. The built-up portion covers 90% of the city's 78.31 sq. km. terrestrial municipal surface, leaving little room for additional retention in case low-lying ecological lands are developed. The urban area suffers from drainage and sanitation problems that reduce hydrological functionality: according to planning documents, storm drainage and sewerage network remain insufficient, and sewerage treatment is minimal, allowing storm water to flow into canals and backwaters without proper processing [32, 33]. Encroachment, dumping, siltation, and weed growth additionally weaken the functionality of canals [34, 43].

The 2018 Kerala flood demonstrated the intersection of water vulnerability, infrastructure weakness, and economic disruption for Kochi: its airport stayed closed for two weeks during this disaster, producing considerable losses [37]. Meanwhile, the backwater environment in Kochi is characterized by adaptation potential, such as in the Kadamakudy wetlands and Pokkali rice-fish cultivation, which combine retention, salinity-resistance, biodiversity, and cultural value [10]. In addition, the Local Biodiversity Strategy and Action Plan and the Mullassery Canal experience suggest the possibility of a participatory approach to water-sensitive planning [18, 25].

A single blue–green prescription cannot solve Chennai's and Kochi's problems because, in terms of urban functions, they are different. Chennai's problems stem from its dependence on coastal drainage and large areas of built-up cover; additionally, Chennai has marshlands, a social exposure to canal corridors, and vulnerability to drainage failure and flooding. Kochi's problems are related to its highly water-rich urban design with backwaters and canals, vulnerability to waste, seasonal water scarcity, heat stress, and drainage failure. Thus, both cities need the adaptation to be made by using blue-green means, but there is a difference in what the function imposed by the urban structure is, see Table 1.

3.3. Projection values and blue–green actions

The projections included in the data are calculated up to the year 2080. For Chennai, the projections imply that its middle-range temperature increase is +1.6 to +2.1 °C, the high-end temperature increase is +4.1 °C, the middle range sea level rise is +0.19 m, the high-end sea level rise is +1.20 m, the middle-range rainfall decline is 1–5%, and its exposure to extreme rain events [14]. For Kochi, the middle-range temperature increase is +2.0 to +4.5 °C, the high-end temperature increase is +4.6 °C, the middle range sea level rise is +0.20 m, the high-end sea level rise is +1.00 m, the middle-range rainfall decline is 15-20%, and it is also exposed to extreme rain events [14].

Table 1. City evidence base.

Dimension	Chennai	Kochi
Coastal setting	Bay of Bengal coast with rivers, tanks, marshland, and Buckingham Canal as major drainage elements.	Malabar Coast and Vembanad Lake setting with backwaters, canals, marshes, ponds, and port-linked urban activity.
Urban scale	Municipal surface expanded from 176 sq. km. to 426 sq. km.; built-up area reached 88% by 2017.	Municipal corporation covers about 98 sq. km.; backwaters under city jurisdiction cover 23.31 sq. km.
Hydrological concern	Loss of wetland capacity, reduced canal function, flood-prone growth, and downstream drainage sensitivity.	Limited storm drains, weak sewerage treatment, direct storm-water discharge to canals and backwaters, and low-lying exposure.
Adaptation assets	Pallikaranai Marshland, Okkiyam Maduvu, Buckingham Canal, tanks, lakes, and recent resilience planning.	Backwaters, Kadamakudy wetlands, Pokkali landscapes, Mullassery Canal, biodiversity planning, and community water initiatives.

There are four classes of action entries. They are national programmes and regulations (AMRUT, Coastal Regulation, Smart Cities Mission); plans on climate change adaptation (the Resilient Chennai Strategy and the Kerala State Action Plan on Climate Change); biodiversity-related activities (the Pallikaranai Marshland process and the Local Biodiversity Strategy and Action Plan); and participatory canal governance initiatives (Buckingham Canal and Mullassery Canal). There are many more activities in each city than those mentioned above, yet, they represent planning efforts made by these cities without mixing them up (Table 2).

Table 2. Climate pressure register.

City	Temperature by 2080	Sea level by 2080	Rainfall-regime change	Extreme rainfall
Chennai	+1.6 to +2.1 °C middle range; +4.1 °C high end	+0.19 m middle range; +1.20 m high end	1–5% decline	Present
Kochi	+2.0 to +4.5 °C middle range; +4.6 °C high end	+0.20 m middle range; +1.00 m high end	15–20% decline	Present

The pressure register establishes the main climatic contrast. Chennai has the stronger high-end sea-level entry, which makes coastal-drainage interaction central. Kochi has both stronger projected warming and a much larger rainfall decline, which means that flood adaptation cannot be separated from heat and dry-period retention. The shared extreme-rainfall entry confirms that both cities need event management, but it does not explain the difference between them (Table 3).

The action register shows institutional breadth in both cases. Each city has one entry in each action class, which means that a simple count of plans and projects would treat Chennai and Kochi as equally covered. HIAP begins from the opposite premise: equal class presence may still produce unequal adaptation adequacy if the climate pressure distribution differs.

Table 3. Blue–green action register.

City	Legal and programme support	Climate planning	Ecological action	Canal governance
Chennai	AMRUT, Smart City Mission, coastal regulation	Resilient Chennai Strategy, 2019	Pallikaranai Marshland, 2012–2020	Buckingham Canal projects, 2019
Kochi	AMRUT, Smart City Mission, coastal regulation	Kerala State Action Plan on Climate Change, 2014	Local Biodiversity Strategy and Action Plan, 2020	Mullassery Canal projects, 2019

4. Analytical procedure

The analytical procedure converts the two-part empirical input set into comparable pressure and cover coefficients. It is designed for cases where city-level projection values and named action entries are available, while detailed hydrodynamic simulations, continuous land-cover time series, and parcel-level delivery records have not yet been harmonized. The calculation is deliberately transparent because its purpose is diagnostic rather than predictive. It identifies which climate dimensions remain less fully covered by the planning portfolio.

For each city i, the climate pressure vector is written as

$$D_i = (T_i, S_i, R_i, E_i), \tag{1}$$

where T_i represents thermal pressure, S_i represents sea-level pressure, R_i represents rainfall-regime pressure, and E_i represents extreme-event pressure. The vector is not a claim that all pressures can be measured with identical precision. It is a practical way to place four distinct planning pressures on a common comparative scale.

Thermal pressure is calculated by first taking the midpoint of the middle-range temperature interval and then averaging that midpoint with the high-end value:

$$\bar{T}_i = \frac{1}{2}\left(\frac{T_i^L + T_i^U}{2} + T_i^H\right), \tag{2}$$

where T_i^L and T_i^U denote the lower and upper middle-range values and T_i^H denotes the high-end value. This treatment gives the high-end value analytical importance without discarding the middle-range interval. It is appropriate for planning because blue–green investments such as wetland protection and canal restoration are long-lived and should not be judged only against low-stress conditions.

Sea-level pressure follows the same midpoint logic:

$$\bar{S}_i = \frac{1}{2}(S_i^M + S_i^H), \tag{3}$$

where S_i^M is the middle-range sea-level projection and S_i^H is the high-end projection. Rainfall-regime pressure is calculated as the absolute mean of the projected decline interval:

$$\bar{R}_i = \left|\frac{R_i^L + R_i^U}{2}\right|. \tag{4}$$

Extreme-event pressure is coded as $E_i = 1$ for both cities because both climate profiles identify exposure to extreme rainfall events.

The continuous pressure values are normalized by the maximum value observed across the two cities:

$$T_i = \frac{\bar{T}_i}{\max_j \bar{T}_j}, \quad S_i = \frac{\bar{S}_i}{\max_j \bar{S}_j}, \quad R_i = \frac{\bar{R}_i}{\max_j \bar{R}_j}. \tag{5}$$

This normalization should be read carefully. A value of 1.000 means the strongest pressure in this two-city comparison, not an absolute upper limit of risk. The benefit of this approach is that it preserves the contrast between Chennai and Kochi while avoiding unsupported universal thresholds.

Composite climate pressure is calculated as

$$G_i = 0.35T_i + 0.35S_i + 0.20R_i + 0.10E_i. \tag{6}$$

The weighting gives primary emphasis to thermal and sea-level pressure because both shape public health, land-use suitability, and long-lived infrastructure exposure. Rainfall-regime pressure receives a lower but substantial weight because it shapes retention, groundwater recharge, and dry-period sensitivity. Extreme-event pressure receives a constant weight because it is shared by both cities in the empirical input set.

The action-cover vector for each city is written as

$$A_i = (L_i, C_i, B_i, P_i), \tag{7}$$

where L_i represents legal and programme support, C_i represents formal climate planning, B_i represents wetland, biodiversity, or marshland action, and P_i represents participatory canal governance. Each class is coded as present when a named action exists. The functional contribution of each action class to each pressure dimension is expressed through the coefficient array

$$\Psi = \begin{bmatrix} 0.20 & 0.45 & 0.15 & 0.20 \\ 0.25 & 0.25 & 0.25 & 0.25 \\ 0.30 & 0.20 & 0.30 & 0.20 \\ 0.10 & 0.20 & 0.15 & 0.55 \end{bmatrix}. \tag{8}$$

Rows represent legal support, climate planning, ecological action, and participatory canal governance. Columns represent thermal, sea-level, rainfall-regime, and extreme-event pressure. The values encode functional expectations. Legal instruments contribute most strongly to coastal and land-use exposure because they regulate development and coastal setbacks. Climate plans are distributed evenly because they can address several pressures through administrative coordination. Ecological actions contribute strongly to thermal moderation and rainfall retention because wetlands and vegetation support cooling, storage, recharge, and ecological continuity. Participatory canal governance contributes most strongly to extreme-event management because canal function depends on monitoring, waste control, maintenance, and neighbourhood acceptance.

For each city and pressure dimension, raw cover is calculated as

$$\bar{K}_{ig} = \sum_{k=1}^{4} A_{ik}\Psi_{kg}. \tag{9}$$

The normalized cover coefficient is then

$$K_{ig} = \frac{\bar{K}_{ig}}{\max_g \bar{K}_{ig}}, \tag{10}$$

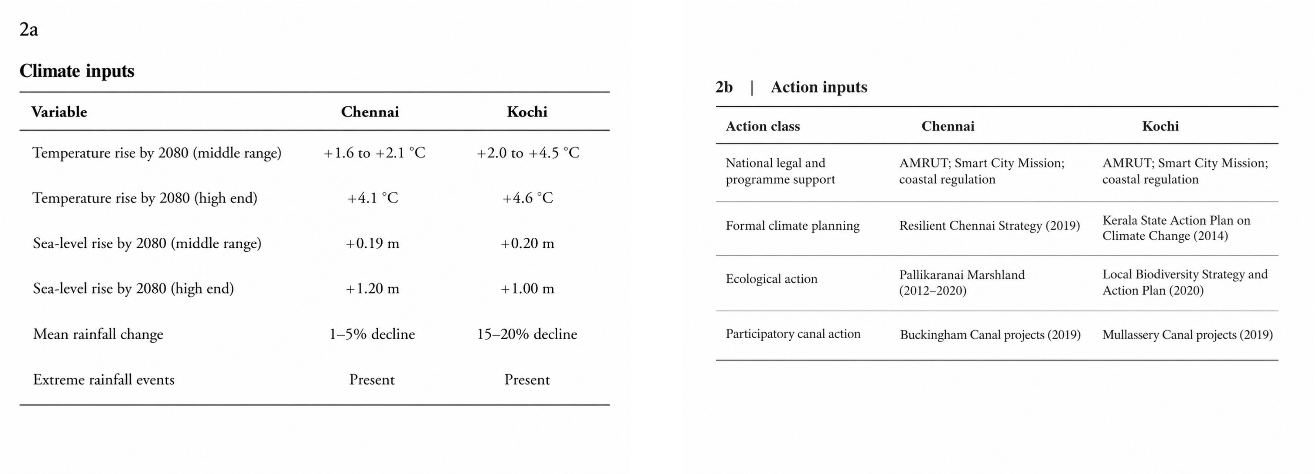
and uncovered pressure is calculated as

$$U_{ig} = \max(0, D_{ig} - K_{ig}). \tag{11}$$

A zero value means that the normalized cover coefficient equals or exceeds the normalized pressure coefficient for that dimension. A positive value means that the pressure remains less fully covered by the present action combination. Weighted uncovered pressure is calculated as

$$H_i(w) = \sum_g w_g U_{ig}. \tag{12}$$

Three weighting profiles are used. Equal weighting assigns 0.25 to each dimension. Coastal-pluvial weighting assigns 0.15 to thermal pressure, 0.35 to sea-level pressure, 0.15 to rainfall-regime pressure, and 0.35 to extreme-event pressure. Heat-dryness weighting assigns 0.35 to thermal pressure, 0.15 to sea-level pressure, 0.35 to rainfall-regime pressure, and 0.15 to extreme-event pressure. These profiles test whether the interpretation changes when planners emphasize coastal flooding or heat and dry-period water stress.



2a

Climate inputs

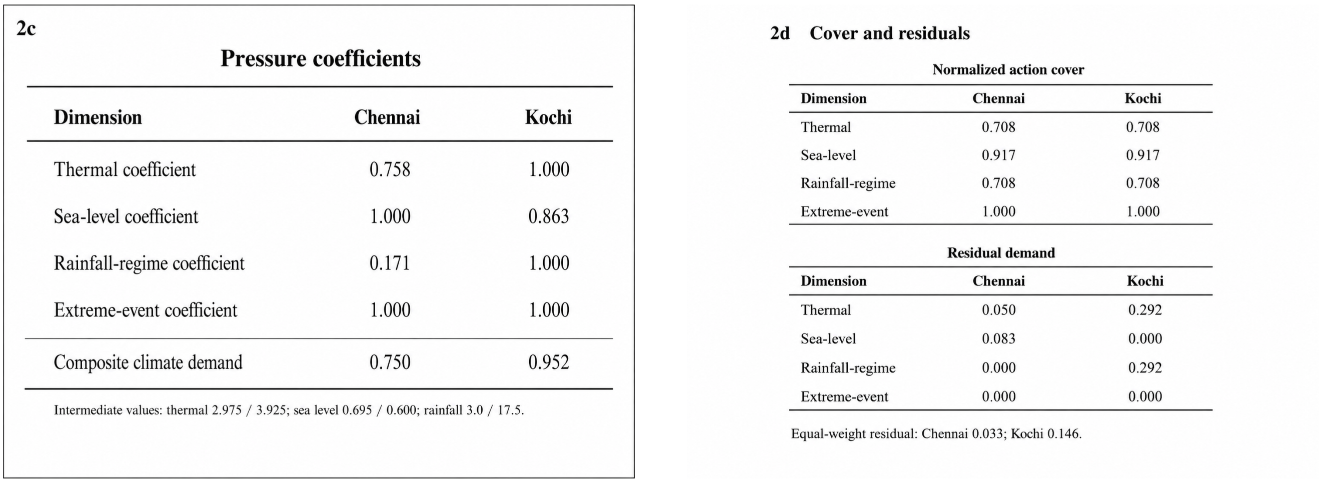
Variable	Chennai	Kochi
Temperature rise by 2080 (middle range)	+1.6 to +2.1 °C	+2.0 to +4.5 °C
Temperature rise by 2080 (high end)	+4.1 °C	+4.6 °C
Sea-level rise by 2080 (middle range)	+0.19 m	+0.20 m
Sea-level rise by 2080 (high end)	+1.20 m	+1.00 m
Mean rainfall change	1–5% decline	15–20% decline
Extreme rainfall events	Present	Present

2b | Action inputs

Action class	Chennai	Kochi
National legal and programme support	AMRUT; Smart City Mission; coastal regulation	AMRUT; Smart City Mission; coastal regulation
Formal climate planning	Resilient Chennai Strategy (2019)	Kerala State Action Plan on Climate Change (2014)
Ecological action	Pallikaranai Marshland (2012–2020)	Local Biodiversity Strategy and Action Plan (2020)
Participatory canal action	Buckingham Canal projects (2019)	Mullassery Canal projects (2019)

(a) Climate entries.

(b) Action entries.



2c

Pressure coefficients

Dimension	Chennai	Kochi
Thermal coefficient	0.758	1.000
Sea-level coefficient	1.000	0.863
Rainfall-regime coefficient	0.171	1.000
Extreme-event coefficient	1.000	1.000
Composite climate demand	0.750	0.952

Intermediate values: thermal 2.975 / 3.925; sea level 0.695 / 0.600; rainfall 3.0 / 17.5.

2d Cover and residuals

Normalized action cover

Dimension	Chennai	Kochi
Thermal	0.708	0.708
Sea-level	0.917	0.917
Rainfall-regime	0.708	0.708
Extreme-event	1.000	1.000

Residual demand

Dimension	Chennai	Kochi
Thermal	0.050	0.292
Sea-level	0.083	0.000
Rainfall-regime	0.000	0.292
Extreme-event	0.000	0.000

Equal-weight residual: Chennai 0.033; Kochi 0.146.

(c) Pressure coefficients.

(d) Cover and residuals.

Figure 2. HIAP input and coefficient register.

The HIAP register in Figure 2 combines the calculations without incorporating any schematic presentation. Panels 2a and 2b show the two sets of entries required by the analysis: the 2080 climate entries and the named blue–green planning actions. Panels 2c and 2d illustrate the appearance of these entries in their normalized and residual form, respectively. This organization helps preserve the clear distinction between climate pressure and planning cover before their comparison.

5. Results

5.1. City differences in climate pressure

For thermal pressure, the calculation results are an intermediate 2.975 value for Chennai and an intermediate 3.925 value for Kochi. After normalization, Chennai obtains a coefficient of 0.758 and Kochi obtains a coefficient of 1.000. The reasons for this distinction include the fact that Kochi exhibits both a higher upper-middle range warming value and a slightly higher high-end warming value. The significance of the finding is that the blue–green portfolio of Kochi should be more stringent in evaluating cooling, shade, evapotranspiration, and thermal refuge capabilities than Chennai's portfolio, although both cities experience thermal pressure.

The sea-level calculation reverses the relationship between the two cities: Chennai has an intermediate sea-level rise value of 0.695 m, consisting of +0.19 m middle-range and +1.20 m high-end estimates, while Kochi has an intermediate value of 0.600 m, corresponding to +0.20 m middle-range and +1.00 m high-end estimates. The normalized coefficients are 1.000 for Chennai and 0.863 for Kochi. The difference does not affect the necessity of Kochi's adaptive response to its rising sea level, but it does indicate that Chennai requires a greater attention to high-end sea-level impacts in connection with drainage and marshland flood overflow as well as canal performance.

Regarding rainfall-regime pressure, Chennai has a relatively weak mid-point pressure value of 3% rainfall decline, while Kochi has a much stronger mid-point pressure value of 17.5%. For the normalized calculations, the coefficients are 0.171 for Chennai and 1.000 for Kochi. The difference alters the interpretation of blue–green adaptation in Kochi, suggesting that water bodies and wetlands should not only be seen as assets for flood conveyance and storage, but also as assets for moisture retention and ecological continuity under changing rainfall regimes.

Table 4. Pressure coefficients.

City	$\bar{T}_i$	T_i	$\bar{S}_i$	S_i	$\bar{R}_i$	R_i	E_i	G_i
Chennai	2.975	0.758	0.695	1.000	3.0	0.171	1.000	0.750
Kochi	3.925	1.000	0.600	0.863	17.5	1.000	1.000	0.952

The coefficients in Table 4 and in Figure 2c reveal that Kochi has the highest composite climate pressure coefficient of 0.952, exceeding Chennai's value of 0.750. The reasons for the difference are that Kochi experiences stronger thermal and rainfall-regime pressures than Chennai, but not more extreme-event pressure or sea-level pressure. The implication for the priority of adaptation is that Chennai requires coastal drainage and cooling measures, while Kochi should focus on cooling and seasonal retention as well as flooding adaptation measures.

5.2. Action cover and residual pressure

The calculation of action cover yields identical values for the two cities, because the two cities contain an equal number of the four action classes: thermal adaptation, coastal protection, seasonal retention, and extreme event management. The normalized cover values are 0.708, 0.917, 0.708, and 1.000, respectively. Although the values do not suggest that there is equal implementation and ecological performance in the two cities, they reveal that, according to the entries selected in the two cities' case studies, both cities exhibit relatively balanced class presence. This result only takes shape in comparison with the climate pressure profiles.

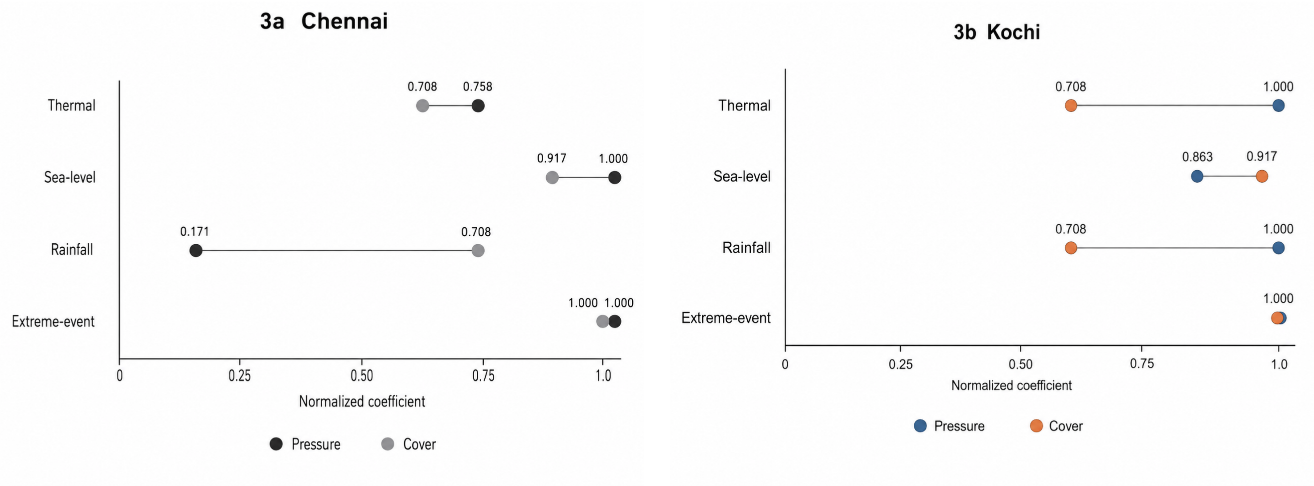
Chennai has residual pressure of 0.050 for thermal pressure and 0.083 for sea-level pressure. For rainfall-regime and extreme-event dimensions, there is no residual pressure, because Chennai's rainfall-regime pressure is weaker and because there is full coverage for the extreme event pressure. Although the thermal and sea-level values are relatively small, they highlight that, with respect to the action classes, Chennai has to consider functional integration among canal projects, marshland, and climate-sensitive open space distribution along coastal areas.

Kochi does not exhibit residual pressure in the sea-level and extreme-event dimensions based on the base calculation, but has residual pressure of 0.292 in the thermal and rainfall-regime dimensions. Based on this finding, there is a mismatch in Kochi, which means that, even though Kochi has legal backing, climate planning, biodiversity actions, and canal participation, its pressure is higher in the thermal and rainfall-regime dimensions. Thus, canals and backwaters should be evaluated not only in terms of flood conveyance, but also moisture retention, shade, evapotranspiration, and other benefits associated with water bodies and productive water-linked landscapes.

Table 5. Uncovered pressure.

City	Thermal	Sea-level	Rainfall-regime	Extreme-event	Equal-weight value
Chennai	0.050	0.083	0.000	0.000	0.033
Kochi	0.292	0.000	0.292	0.000	0.146

As shown in Table 5 and Figure 2d, adaptation cannot be assessed only in institutional terms: although the two cities have all action classes, the normalized uncovered pressure in Kochi is almost four times higher than in Chennai. This conclusion does not rest on institutional absence, but on functional mismatch. Since Kochi has relatively high thermal and rainfall pressure, but not in relation to action cover, and since Chennai has lower uncovered pressure in sea-level and thermal dimensions, there is functional mismatch.



(a) Chennai.

(b) Kochi.

Figure 3. Pressure–cover comparison.

The graphs in Figure 3 illustrate clearly that, unlike a simple project inventory, the mismatch arises because of the relative mismatch between action cover and climate pressure. With respect to Chennai, the cover coefficient is very close to the pressure coefficient in the thermal and sea-level dimensions, but rainfall-regime pressure is weaker than the corresponding cover value. For Kochi, on the other hand, thermal and rainfall pressure values of 1.000 exceed the cover value in both dimensions, producing the highest uncovered pressure dimensions in the analysis. The shared extreme event pressure dimension, however, shows perfect overlap.

5.3. City-specific interpretation

The results of the HIAP analysis reflect the post-flood planning trajectory of Chennai, following the 2015 floods. As a result of the flood, a government audit highlighted that there were weaknesses in the land use planning process and development control measures, as well as in flood management measures [6]. Following the flood, Chennai developed its Resilient Chennai Strategy, and identified 52 water bodies for restoration, including rivers, canals, marshlands, tanks, and lakes [9]. Among them, Pallikaranai Marshland received particular importance, as it drains storm-water flows from several urban sectors, being hydraulically connected to Okkiyam Maduvu and Buckingham Canal [45]. The small residual pressure suggests that the marshland system needs to be evaluated as a coastal drainage system, rather than a collection of individual restoration sites.

With respect to the Buckingham Canal in the same city, the result reveals that the planning effort should be accompanied by another interpretation dimension. The Buckingham Canal is an old waterway, but its current urban function has been severely compromised through urban encroachment, siltation, and pollution. The Eyes on the Canal initiative focused on improving the condition of 3.5 km of the canal length, through public engagement, urban design, and municipal validation of initiatives [17]. According to HIAP, such actions constitute valuable canal governance, because they involve the maintenance, waste control, monitoring, and acceptance of local communities in regard to canals during extreme events. The residual pressure suggests, further, that the canal renewal should also include shade and other features for public space cooling.

Kochi's results require a different interpretation. First, the State Action Plan on Climate Change highlighted that rising sea levels and urban flooding were key challenges for Kochi [33]. Second, the Local Biodiversity Strategy and Action Plan included canals, backwaters, climate change, traditional Pokkali rice-fish agriculture, and Sustainable Development Goals in the local urban plan [25]. Finally, the Mullassery Canal Initiative, facilitated by EnteKochi, involved participative surveys and urban lab activities for water body and public space planning [18]. Despite the institutional breadth of actions in these initiatives, the uncovered-pressure calculation indicates that the breadth should be matched by seasonal retention and thermal adaptation performance.

The rainfall-regime pressure in Kochi requires a reinterpretation of water bodies. Traditionally, water bodies would play the role of conveyance and storage for floods. But based on the HIAP results, the role must also extend to include retention, recharge, evapotranspiration, shade, water quality, ecological continuity, and livelihood support during dry periods. In Kochi, this implies that Kadamakudy wetlands and Pokkali fields become crucial, because they can serve as productive use, ecological continuity, and salinity-tolerant assets. The thermal pressure, finally, supports a similar conclusion about canals: their edges should produce shade and cool walkways.

5.4. Sensitivity analysis

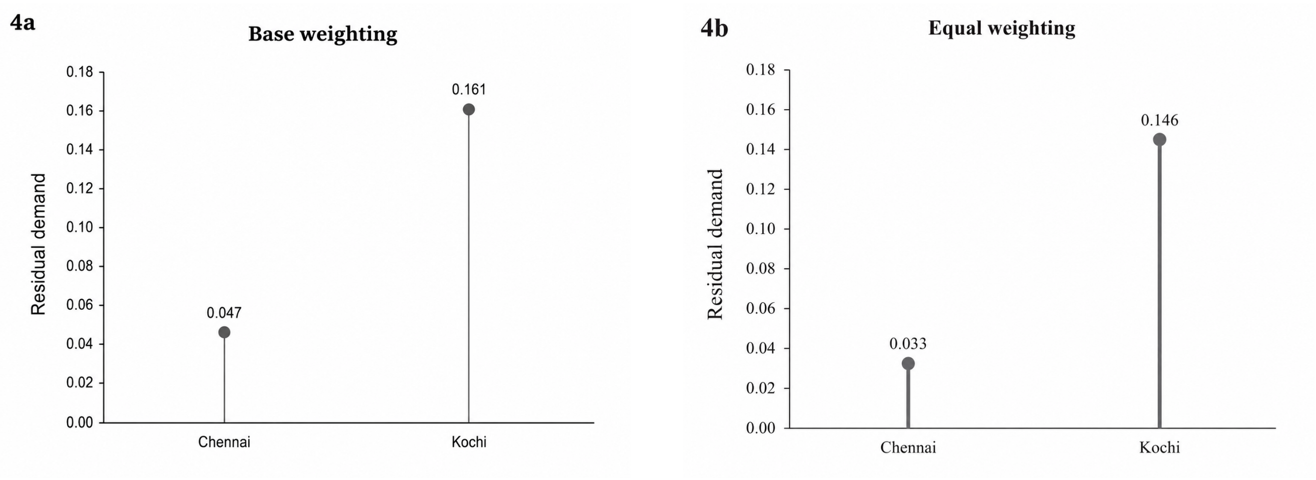
The sensitivity analyses show what happens if planners choose a different pressure group as their priority. In equal weighting, Chennai exhibits uncovered-pressure of 0.033, whereas Kochi exhibits 0.146. With respect to coastal-pluvial weighting, both cities obtain lower values, namely, 0.037 for Chennai and 0.088 for Kochi. The explanation is that, in this test, the higher residual pressure in Chennai, which belongs to the sea-level dimension, affects the interpretation, but Kochi's residuals fall outside of this dimension and extreme events. By contrast, heat-dryness weighting highlights the differences most strongly: Chennai obtains a residual of 0.030, whereas Kochi obtains 0.204.

Table 6. Weighting tests.

City	Equal weighting	Coastal-pluvial weighting	Heat-dryness weighting
Chennai	0.033	0.037	0.030
Kochi	0.146	0.088	0.204

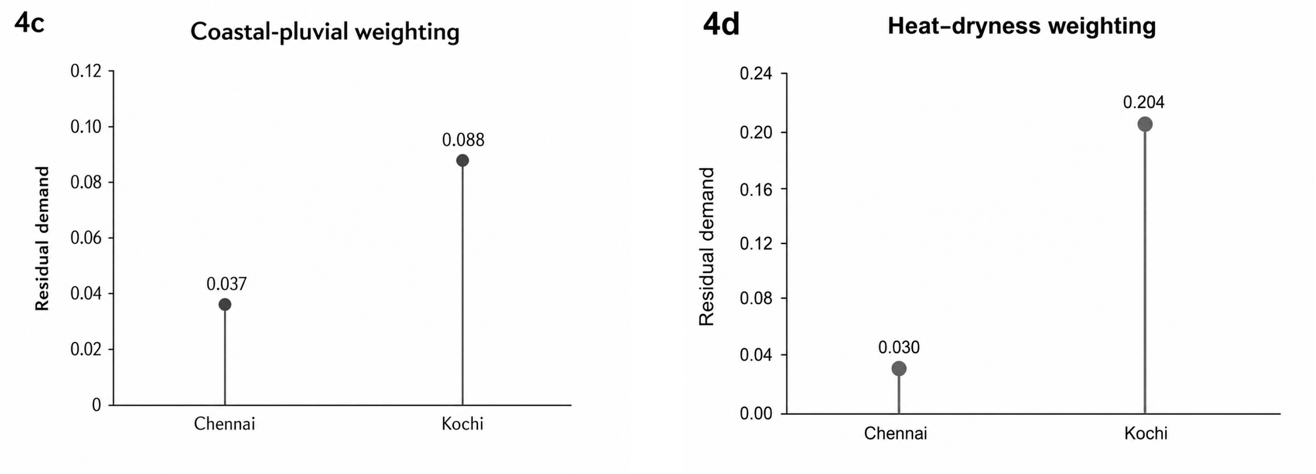
The four panels in Figure 4 validate the direction of comparison according to each of the weighted profiles. Kochi is always ranked ahead of Chennai in the profiles, with a particularly wide gap appearing when heat and rainfall decline pressure receives greater weight. The coastal–pluvial profile decreases the difference by putting emphasis on dimensions with relatively low residual pressure for Kochi, whereas the heat–dryness profile increases the difference by emphasizing Kochi's uncovered dimensions.

These weighting results along with the findings in Table 6 show that the comparative finding is robust to sensitivity tests. Kochi always has a higher residual pressure in all three of the profiles, with a particularly large residual pressure emerging when heat and rainfall decline are emphasized. The value of Chennai's uncovered pressure is only marginally higher than zero because it has smaller residual values distributed over two dimensions. From a practical perspective, Chennai should develop additional criteria relating to coastal and thermal issues as well as add these criteria to the existing blue–green plans. The recommendation for Kochi is similar; its planning effort should incorporate criteria related to retention and heat pressures, which it has not covered yet.



(a) Base weighting.

(b) Equal weighting.



(c) Coastal–pluvial weighting.

(d) Heat–dryness weighting.

Figure 4. Residual demand under alternative weighting profiles.

6. Discussion

6.1. Functional adequacy and institutional breadth

It is shown that institutional breadth and functional adequacy are distinct qualities. Both cities benefit from national programmes, legislation, formal climate plans, ecological interventions, and participation in canal planning and restoration. In other words, the breadth of their adaptation action portfolio is substantial. But even with equal institutional breadth, the two cities show unequal pressure coverages. In particular, both cities' adaptation action structure consists of the same four classes, although Chennai is characterized by small uncovered thermal and sea-level pressure while Kochi has considerable uncovered thermal and rainfall-regime pressures.

For municipal practice, the importance of this conclusion is clear. Climate adaptation planning is often associated with evidence-based action portfolios. Project inventories, strategy documentation, and flagship interventions provide a necessary toolset. But there is always a risk of ignoring pressure-specific gaps within such a project list. An example of this problem can be a flood management intervention that does not address thermal pressure and, therefore, is unlikely to provide shaded areas for pedestrians. Another example is a biodiversity action aimed to protect certain wetlands while neglecting rainfall management issues in other parts of the city. Likewise, coastal regulation may be effective in some cases but insufficient in others depending on implementation problems and local water management. Therefore, it is important to evaluate adaptation action against pressure using methods such as HIAP that do not require all modelling layers at the very start of the planning process.

In addition, the method facilitates transparent public discussions. Since all coefficients and weighting profiles are specified in the calculation process, municipal experts can debate the value of coefficients based on additional evidence and adjust them. The goal of the calculation is not to close down a technical decision but rather to facilitate dialogue about the functional needs in a city. This can be particularly useful for coastal cities with memory of recent floods. Heat, dry-period pressure, and ecological preservation can easily be neglected under the influence of flood pressure.

6.2. Chennai: coast and storage, and cooling potential

The findings regarding the uncovered pressure dimensions in Chennai suggest a concentration on coastal–drainage interaction and thermal moderation. Indeed, Chennai has been paying increasing attention to the importance of water body preservation following major flooding events in the city [9]. Identification of rivers, canals, marshlands, tanks, and lakes for restoration indicates that Chennai now recognizes that these water bodies should no longer be considered mere left-overs. The significance of Pallikaranai Marshland and Okkiyam Maduvu lies in their importance for downstream storage and conveyance, as they contribute to the overflow path from Buckingham Canal and other outlets towards the ocean [45]. The sea-level coefficient demonstrates that any evaluation of this chain cannot be done only by taking present drainage gradients. High-end sea-level rise would reduce the efficiency of the downstream discharge and increase the need for upstream retention and regulated release.

The thermal residual coefficient is lower than sea-level, but this does not imply that it is not important. On the contrary, Chennai is characterized by high built-up fraction and low provision of green space. For this reason, Chennai must focus its attention on thermal pressure when developing its urban adaptation plans. In particular, the city should develop its marshland protection efforts and tank restoration and link these actions to other elements of urban cooling such as canal restoration, shaded pedestrian paths, urban forest planting, and floodable parks.

Photographic examples highlight the importance of the above considerations for the urban climate adaptation agenda. Coastal edge and Buckingham Canal panels suggest the significance of assessing sea-level rise impact on coastal discharge. The next two images, related to Pallikaranai Marshland and open-space deficit, suggest the significance of the thermal pressure and the need to provide cooling open spaces in the city.

The significance of social safeguards in this context is evident. Coastal edges and riverbeds usually contain vulnerable settlements whose exposure is determined not by flood hazards alone, but rather by housing shortage and pressure on construction land markets. Therefore, flood-based adaptation may shift climate risks to poor settlements that suffer from inadequate resettlement and lack of basic services [8]. Adaptation practices recommend addressing distributive effects of nature-based solutions by incorporating community participation and maintenance efforts [47]. In the case of Chennai, Eyes on the Canal project provides a good opportunity for initiating such collaboration [17]. Next, it will be critical to translate this involvement into maintenance and waste management.

6.3. Kochi: water abundance and retention need

Uncovered-pressure findings in the case of Kochi indicate the importance of water abundance and retention need. Although the city is characterized by the prevalence of backwaters, canals, marshlands, and ponds, Kochi's uncovered pressures appear to be related to heat and rainfall-regime decline. Thus, a blue–green adaptation plan in Kochi can only be evaluated by its ability to ensure year-round water retention, wetland moisture, reduction of heat impacts, improvement in water quality, and productive retention landscapes.

Local Biodiversity Strategy and Action Plan of Kochi City Municipality appears to be an appropriate starting point for addressing uncovered pressures [25]. Indeed, this plan highlights the connection between biodiversity, canal maintenance, backwater management, climate change, and traditional cultivation. Kadamakudy wetlands and Pokkali fields represent a combination of salinity-adapted production, water retention, biodiversity conservation, and productive landscapes. Preserving these areas can prevent the necessity of excessive dependence on engineered flood channels.

As seen from the visual examples, water bodies are abundant in Kochi. Nevertheless, HIAP findings suggest that

Kochi should be focused on heat and rainfall decline. To achieve this goal, it is important to combine biodiversity protection with retention and water-quality measures within the backwaters, canals, and wetlands. In addition, it would be important to protect the productivity of the wetland edges by creating small urban parks.

Mullassery Canal can be used as an illustration for demonstrating the social dimension of Kochi's adaptation need. During a participatory workshop, residents identified the necessity of reducing waste, eliminating weed growth, and ensuring access to the water bodies [18]. From this perspective, canal management involves waste removal, vegetation removal, and public access to the water channels. In terms of HIAP interpretation, canal visibility, public access, maintenance, and retention capacity can be combined into a complex adaptation function.

6.4. Implications for national urban policies

The comparison has significant implications for national urban programmes. Indeed, AMRUT, the Smart City Mission, climate-smart assessment frameworks, and national coastal policies offer municipalities the means to understand the potential of urban water bodies in terms of adaptation [1, 19, 20]. But even if such national policies mention specific functions of water bodies as part of adaptation, these functions are not always distinguished. For example, restoration of lakes, improvement of drains, and increase in green areas can lead to a visible number of adaptation-related projects and interventions. Still, this does not necessarily ensure that all required functions of water bodies will be covered appropriately.

HIAP can be employed in this respect as a tool for preliminary pressure evaluation. Namely, the method provides a pressure-specific diagnostic step before any significant investments can be fixed. If the case of Chennai is taken as an example, then HIAP would justify the need to estimate the impact of sea-level rise on coastal discharge, the ability of the marshland storage system under intense precipitation, and the accessibility of cooling open space in dense neighbourhoods. In Kochi, HIAP would justify the estimation of wetland moisture, water quality, access to the canals and backwaters, productivity of the wetland edges, and water retention capacity under rainfall decline.

Moreover, the method facilitates an adaptive sequence. The first step would involve the use of existing registers of projections and actions. Next, land cover change, observation of flooding and rainfall intensity, and hydrological modelling could become an addition. Each new information layer will allow the revision of the coefficients. The adaptation function will be kept the same: pressure cover comparison should guide further adaptation decisions.

6.5. Interpretation limitations and municipal application

The presented method has some clear limitations, but it can be applied at the municipal level. First, HIAP involves the relative normalization of projections and actions, so it generates city-specific coefficients. The rainfall-regime value of 1.000 in Kochi means that Kochi has greater rainfall pressure than Chennai within this case set. Zero value of the rainfall pressure dimension in Chennai implies that cover in Chennai exceeds demand under the selected coefficients. These statements must be kept in mind whenever HIAP will be employed.

Second, the value of pressure cover coefficient is calculated based on the presence of classes in the action plan. In this sense, the method does not distinguish a named strategy from its implementation, and a strategy does not have an estimated budget or other characteristics. As a consequence, the method only suggests areas where additional investigation may be necessary. Therefore, it is important for future applications to assign grades to action implementation based on budget, legal force, social acceptance, maintenance efforts, etc.

Nonetheless, HIAP is useful even for this limitation since many municipalities currently possess climate projections, action plans, strategies, and other documents related to adaptation action. Thus, HIAP allows municipal experts to use their documents for a pressure-specific diagnosis.

7. Conclusion

The paper has produced a clear result. Namely, the combination of projection values and named adaptation actions at the city level allows the researcher to conduct the pressure-specific adequacy evaluation of a municipal blue–green adaptation plan. In the case of Chennai and Kochi, the analysis shows that these cities have extensive institutional coverage in terms of adaptation plans and strategies. But their uncovered pressure profiles prove that these plans are not equally relevant to actual pressure.

The main findings of the analysis indicate that Chennai adaptation efforts are mostly concerned with coastal interaction and thermal moderation. Its high sea-level pressure implies that drainage from Pallikaranai Marshland, Okkiyam Maduvu, Buckingham Canal, tanks, and lakes should be understood as a single channel. Moreover, the uncovered thermal pressure shows that Chennai should invest in open cooling spaces as well as in shaded pedestrian lanes. Social safeguards will be necessary to implement this agenda due to the presence of vulnerable populations at the canals.

Similar conclusions emerge for the city of Kochi, although in a slightly different form. Namely, the analysis reveals that the city faces high pressure in heat and rainfall decline, although the coverage ratio in rainfall is zero. Thus, it is important to go beyond flood-based adaptation and focus on canals, backwaters, Kadamakudy wetlands, and Pokkali fields. The city will also need to address water quality and weed growth as well as implement productive wetlands with cooling capacity.

Thus, the method has provided an example of how pressure–action relationship in blue–green adaptation can be estimated. HIAP is a good diagnostic tool for municipalities possessing city-level climate projections and adaptation documents since these inputs are required to employ the method. After applying HIAP, the next steps may include hydrological modelling, social surveys, and evaluation of existing action implementation.

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