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Research Article

Design response to rising sea levels in the Maldives: A study into aquatic architecture

Ahdha Moosa, Khoa Do, Emil Jonescu*

School of Design and the Built Environment, Curtin University, Perth, Australia

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Abstract Climate change and rising sea levels present immediate threats to humanity. However, the global catastrophe fails to generate sufficient action. Subject to total submergence within 80 years, this study undertakes an iterative design process seeking sustainable adaptation strategies for the coastal island nation of the Maldives, specifically, Malé, its capital, which exists under a "state of alert" by order of government. Research methods include literature reviews, site analysis, mapping, and iterative design processes to develop an implementation framework strategy. Infrastructure concepts are presented as speculative images with context-specific spatial relationships and functions. Concepts do not intend to represent a conclusive prototype, rather, an ideation—a solution-based discourse among key audiences highlighting the need to act decisively and adaptively.
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1. Introduction

Rising sea levels (RSLs) present a devastating prospect of cultural and societal collapse yet to be experienced by modern civilization. Scientific agencies worldwide continue to research the ongoing effects of RSLs and monitor and model the short-, medium-, and long-term morphologies of communities at high risk. The Maldives is a tropical nation located in the Indian Ocean. This nation was chosen as a case study because it is a highly populated country under imminent threat of RSLs. Such threat may lead to anything from localized flooding to total submersion within decades as evidence suggests. This situation is likely to spawn an entirely new form of refugeeism: climate change refugees.

In response, a number of remedies have been explored, including retreating, adapting, and barricading and fortifying (from localized to urban scale) the entire coastlines. In many other countries where the threat is less imminent, nothing has been done. Climate change deniers exist in the highest order. The current United States President Donald Trump has suggested that climate change is a "hoax," stating "I don't believe it" (BBC, 2018: para. 1). This notion indicates the clear acceptance of RSL measures from complete denial to moderate consideration. Mediocre and

* Corresponding author.
E-mail address: e.jonescu@curtin.edu.au (E. Jonescu).
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disproportionately inadequate countermeasures have been considered and implemented to date, given that RSLs likely represent systematic damage to infrastructure and risk to life of many people.

However, the lived reality in many low-lying nations with affected communities and governments sees that universities and research agencies continue to pursue viable and sustainable policies and action planning. During the literature review process, we explore several case studies with the view that they may inform decision making relevant to the research objectives. Although a case study likely meets all the criteria for establishing a Maldivian model, we select case studies with key relevant and transferable attributes determined through an analytical process (Research Methodology).

Copenhagen, Calcutta, Venice, and Vancouver are just some examples (among many) of cities pressured by RSLs to act decisively and imminently. The threat will not be reversed by a downshift in the pace at which climate change occurs, meaning that what has transpired cannot be undone. No universal remedy is applicable to all global circumstances. The sheer scale and diversity of the variables alone (e.g., geographical, economic, and political factors) ensure that humanity must encounter and adapt countermeasures to match each situation.

This study suggests that RSLs highlight a critical juncture for humanity and explores and identifies solutions through the disciplines of architecture and construction management. Specifically, this study considers limiting parameters and novel opportunities for critical design thinking. This research also formulates a design brief and subsequent transposition to the manifestation of a prototype model that seeks to lessen the effect of extensive but necessary population mobility. Under such circumstances, safety and existence dictate as priorities for those under immediate pressure to relocate and resettle. This notion does not dissuade from the significance of environmental, economic, living, sociocultural, and social and geopolitical factors. However, from the perspectives of people in danger, self-preservation and family are undoubtedly primary concerns. The likely three key strategies against RSLs are to (1) defend, (2) isolate and retreat, or (3) relocate those affected people.

Defensive techniques, having been employed in the Maldives through seawalls and artificial reefs, have been discounted because of their short-term and reactive nature. The whole life cycle costing to undertake defensive countermeasures against RSLs into perpetuity is virtually incalculable. Given the number of uncontrollable variables, this option presents a great risk and is considered unfeasible. Isolating and retreating are largely ineffective solutions because of the lack of high ground. Once the deluge of water breaks past the outer wall of the reef, extensive flooding and submersion occur. Defensive techniques are also generally untenable. Therefore, adaptive relocation is considered the optimal long-term, semipermanent to permanent transition and sustainable approach. On this basis, the design of a speculative prototype is required and entails infrastructure for transition and habitation that aims to facilitate the processes required for community re-establishment. A spatial function that considers aquatic architecture, urban growth, and renewal and can adapt to further shifts in climate and RSLs is considered. This concept is studied by analyzing examples of "as-built" infrastructure and the methods employed to counter RSLs in other contexts and countries. This initiative is a part of a multiphase architectural implementation plan to provide resilient urban growth in the Maldives relative to RSLs. Furthermore, this paper presents a corresponding research framework for initiating a first phase as part of a two-phase research by design dissertation project.

1.1. The Maldives

The Maldives features an average of 1.8 m elevation above sea level and is the "flattest country on Earth" (Union of Concerned Scientists, 2011: para. 1). This small island nation in the southwest of the Indian Peninsula is made up of just under 1300 islands and is vulnerable to a paucity of natural defense against tidal fluctuations. Malé, the nation's capital, is at a great risk from RSLs due to development extending to a narrow shoreline. The city is solely dependent on limited alternatives to counter such risks, is helplessly unprotected, and mainly relies on human ingenuity—the construction and ongoing integrity of a tetrapod wall (Naylor, 2015). This built infrastructure represents Maldivian interdependency on infrastructure solutions to complex and wicked problems for survival. However, this effort represents a defensive mechanism, which offers a short-term "bandaid" solution that merely ameliorates relentless tidal wave impact. The government must "buy time" to conceive and implement a bespoke, long-term strategy irrespective of its temporary nature. Leaders should not be appointed where they do not understand or accept the status quo, or where they have no commitment to plan for emergency action. At this point, whether certainty surrounding permanent solutions exist without resorting to extreme and unconventional measures is questionable. Some people may even refer to certain propositions as preposterous, whimsical, or eccentric. The only certainty is that RSLs will plunge many nations into genuine humanitarian crises regarding infrastructure, food, and economic security, all of which are worthy of deliberation and consideration.

The United Nations Development Programme (United Nations Development Programme, 2014.) asserts an obligation for all, in their respective capacity, to become resilient and agile to adapt to the implications of climate change. The physical implementation of resilient and sustainable infrastructures that provide a strong response to the Maldives, and similar to that of other nations, is necessary to attest to the critical and urgent need for novel approaches and methods of development. This research undertakes a critical analysis and review of case studies that have employed novel techniques and applications of "aquatic architecture" to counter RSLs in response to an urgent call for action and to help formulate an informed design brief. The scope aligns with the Maldivian "retreat and relocation framework" with additional robust application of architectural design principles that inform adaptive and sustainable infrastructure vernacular to the highly vulnerable city of Malé.

2. Literature review

Proximity to water and the relationship of individuals with it have helped shape and advance civilizations, particularly the morphology of urban environments and their interface with waterways. The natural gravitas to develop along waterways for access, transport, leisure, trade, and defense highlights just a small sampling of how society and culture develop and mature through interactions with water (Roggema, 2012; Wylson, 1986).

To date, the need for compelling action to avert catastrophe in low-lying communities for survival has been inadequate at best. Highly populated delta communities, which are situated in close proximity to the coastal fringe, have recently commenced gradual shifts away from coastline areas, sometimes following generations of living alongside water. The RSLs are not reversible. Given the immediacy and relationship, vast populations (and generations) share with the waterfront (whether of choice, circumstance, or for their livelihood); such shifts away from this connection with delta areas will have significant communal and cultural effects (Jevrejeva et al., 2016).

Numerous studies identify trending patterns that support predictions of global temperature increases as much as 2 °C above the pre-industrial level (Commonwealth Scientific and Industrial Research Organization [CSIRO], 2018; Intergovernmental Panel on Climate Change [IPCC], 2016: pp 24–25) with RSLs projected to peak to an "unacceptably high" level between 2040 and 2050 (Jevrejeva et al., 2016: p 13342). The National Academies of Sciences, Engineering, and Medicine (2005: p 1), attesting to the IPCC 2001 and the UN Framework Convention on Climate Change, concurred that "significant global warming is occurring" and that:

> Evidence comes from direct measurements of rising surface air temperatures and subsurface ocean temperatures … and from phenomena, such as increases in average global sea levels, retreating glaciers, and changes to many physical and biological systems.

Jevrejeva et al. (2016: p 13342) highlighted that an "average global ocean rise of 20 cm" is projected as a result of climate change, and 90% of delta areas are set to experience great effects. Widespread destruction and devastation are forecasted for the underprepared with little reprieve. The problem is envisaged only to worsen with foreseeable global temperatures set to increase by 2100. A forecast rise of 5 °C equates to a further 0.9 m rise in sea levels in most areas and significantly high rises in extreme cases for highly at-risk areas (Jevrejeva et al., 2016). Fig. 1a (left) illustrates these projections relative to most countries in the "South, Southeast, and East Asia" regions that are likely to experience the high immediate effect of density and urban populous in delta areas (Nicholls and Cazenave, 2010: p 1519). Fig. 1b (right) also outlines global projections of RSLs set against increases in temperature. Images A, C, and E are median projections at 50%, while B, D, and F indicate (to a great extent) projections to 95% and increases relative to 1986–2005 with little change in CO_2 emissions by 2100, all of which are read within Representative Concentration Pathways (RCP8.5) (Commonwealth Scientific and Industrial Research Organisation, 2011). Images A and B, C and D, and E and F depict 2 °C, 4 °C, and 5 °C increases, respectively (Moosa et al., 2018).

The Royal Society's (2014) report on resilience to extreme weather outlines some key recommendations. These recommendations corroborate the claims to the *National Geographic*, which anticipate that hundreds of millions of people worldwide, particularly those in highly populated delta areas, are at a great and imminent risk of RSLs (Nunez, 2019). Strategic plans must be prioritized to protect these communities and, in some instances, indigenous civilizations. "Coastal communities … in the developing world … small island states" and "tropical coastal ecosystems" will have limited time after mid century to adapt to these rises (Jevrejeva et al., 2016: p 13342). Roggema (2012) supported this notion by proposing the need to develop proactive measures and infrastructure that is adaptive to the unpredictability of climate-related RSLs.

Industries that provide the very fabric of national wealth, convenience, economic growth, and stability have been and continue to be among the primary drivers of climate change. In this context, current thinking, systems, or institutions, which have been attributed to the current state of RSLs, cannot garner the necessary fortitude to affect sufficient changes to remedy the situation (Roggema, 2012: p 6). Acting appropriately in keeping with a relevant time frame requires governance and a societal paradigm shift. Historically, attitudes to change at such magnitude are typically passive, and this shift is of critical concern to the prospect of seeking viable and long-term solutions (Moosa et al., 2018). Therefore, the small sampling of current initiatives (case studies) proven to mitigate RSLs in varying contexts and under diverse conditions verify that a paucity of action prevails (Roggema, 2012).

2.1. Existing situation in malé

The structural form of Malé and its lagoons comprise a mere sequence of reefs; tidal activity and natural sedimentation of materials, such as sand build-up and deposits, add to its composition (Naylor, 2015: p 730). The islands contain a 750-km circular stretch of atolls ordered in a relatively linear cluster (Betzler et al., 2013; Naylor, 2015: p 729). Although these atolls are now heavily eroded and mostly ineffective, they have formed a natural barrier from tidal activity—the reef providing a defensive structure from surges.

Malé (Fig. 2a) has experienced significant population growth and urban sprawl that extends to its coastline. Accordingly, expansive landfill activities have claimed an increase in useable area from the 1970s to the 1980s (Naylor, 2015). The "necessary" coral reef mining during this time to allow for this expansion has inadvertently reduced the natural defenses of the island. Nevertheless, the effects of climate change and RSLs would not have been well understood some 50 years ago (Moosa et al., 2018). Hulhumalé (Fig. 2b) is an example of an artificial island entirely conceived to provide for the expansion of Malé. However, its creation still does not address the ongoing effects of RSLs and tidal activity in the region.

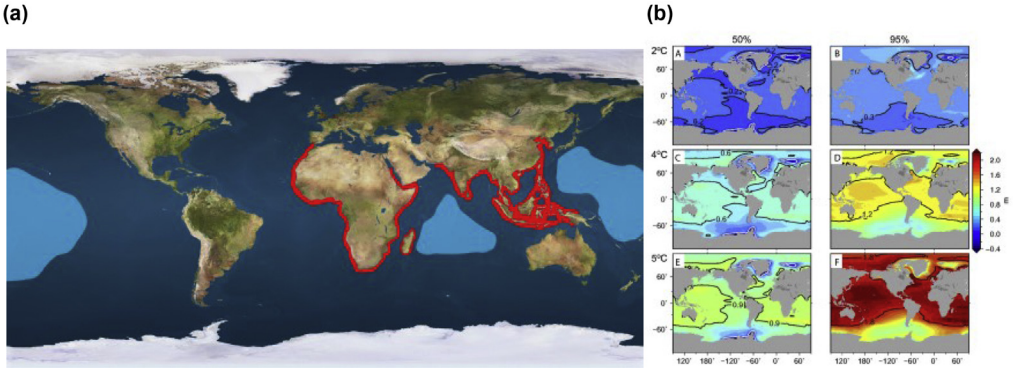

Fig. 1 (a) regions most vulnerable to coastal flooding due to RSLs. Delta cities with low-lying coastal zones and high populations (red) and small Indian and Pacific Ocean islands (light blue) are at extreme risk (Authors, 2020; adapted from Nicholls and Cazenave, 2010); (b) regional projections, 1986—2005 (Jevrejeva et al., 2016).

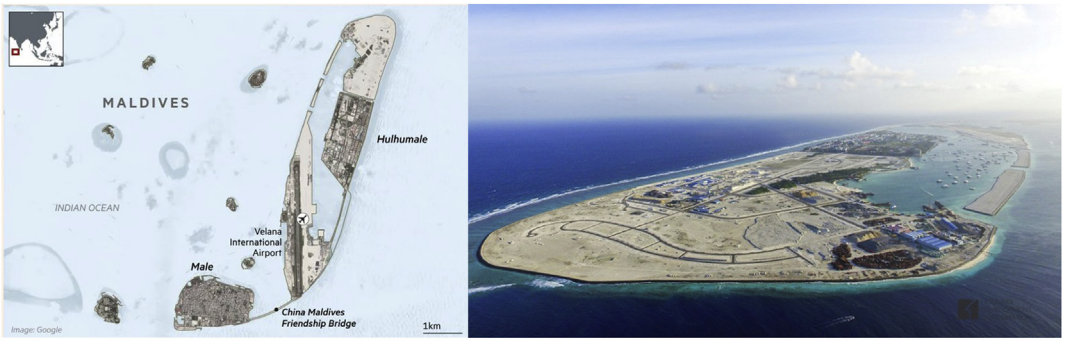

Fig. 2 (a) map of Malé, land reclamation now completely urbanized with "higher" (artificial) elevation (Maldive Times, 2019); (b) Hulhumalé Island (Housing Development Corporation, 2016).

After the flooding in 1987, a tetrapod seawall was built (Fig. 3), thereby providing an artificial reef fortification that encircles the island to counter the risk of similar events (Naylor, 2015). This structure is just one component of a great fortification plan intended to mitigate local ecosystem damage and delay the active coetaneous effects of climate change. Further fortifications are considered neither sustainable nor feasible as long-term options to combat RSLs. Adaptive strategies to meet existing needs must be met in an entirely new and sustainable framework.

2.2. Urban resilience

The term "urban resilience" can be considered the proportionate adaptation required of a society and its built environment facing hardship or misfortune (Sanderson et al., 2016). This definition is not specific to natural forces or consequences imposed by community activity. However, whether local or urban, misfortune leads to a human need or condition and highlights opportunities for the disciplines of construction management and architecture to contribute, in some way, to seeking novel solutions

Fig. 3 Satellite view and map of Malé depicting the tetrapod seawall (Ilyas, 2019).

in confronting and adapting to spatial crises and habitation challenges. On this basis, professional disciplines clearly have a role to play and can significantly contribute to the academic, industrial, and societal discourse and landscape, but only in part. Irrespective of the strategy, whether *defending* with walls, *retreating* where possible, or *adapting* cities to remain livable and responsive to the environment (Moosa et al., 2018), this mechanism is the way in which disparate communities in isolation and society as a whole reciprocate to the imminent need for shifts in lifestyle, habits, trends, culture, and comfort that will outline their fate.

2.3. Aquatecture

"Aquatecture" incorporates water as a primary consideration in an architectural strategy (Wylson, 1986). Watson and Adams (2011) concurred with this definition and applied this line of inquiry to develop guidelines for intelligent water design, celebrating the inclusion of water as a resource and provider of opportunities in design. Barker and Coutts (2016) added to this body of knowledge and considered that aquatecture regards, as their text of the same name dictates, *Buildings and Cities Designed to Live and Work with Water*. In the book, they highlight England's first floating village for London's Royal Docks, a primarily autonomous development by dRMM architects fully surrounded by water, thereby providing all the amenities necessary. This model includes reliance on water travel rather than roads and is pro-pedestrian and pro-cycling. Such situation is an example of the relationship between water and architecture and how urbanization and RSLs shape the way designers must respect water through design. Other schemes are planned for Edinburgh, and many other examples exist throughout Europe, particularly in lower-lying Holland and Amsterdam (Eve, 2014).

The international "Aquatecture 2018 Architecture Competition" was recently held. Nevertheless, similar to the design of a visually striking, well-lit, and new carceral facility, such as the Justice Center Leoben in Austria, the ability of architects to convey a visual grammar of hope, beauty, and adaptiveness almost exudes a desirable quality wherein one may wish to dwell.

3. Research methodology

3.1. Qualitative research

Iterative design is a research methodology that incorporates qualitative methods. This approach supports a research by design process according to a bricolage framework (Fig. 4), particularly relative to concepts such as "aquatic architecture" within the Maldives.

Relevant and appropriate aspects of this understanding have informed the spatial and functional relationships of the design proposal (Groat and Wang, 2013). To date, the research has identified significant quantitative data relating to RSLs; however, their influence and application requires interpretation, distillation, and iteration through a qualitative and peer-reviewed iterative design process (Moosa et al., 2018).

3.2. Design methods (research by design)

Identifying background studies using a literature review and a case study critique partially informs the iterative prototype-testing design process. This approach supports appropriate benchmarking to existing exemplars and provides an in-depth understanding of design considerations against similar constraints. The design expectation management of outcomes intends to be within the scope of existing frameworks of knowledge. Iterative design allows for ideas to be tested, peer reviewed, and further evolved. An ongoing refinement process of observations, findings, and applied outcomes will be presented and discussed in Section 3.1. The collected data are analyzed to explore opportunities in developing solutions to a main objective through an architectural—infrastructural typological proposal. Research by design consists of architectural explorations through experimentation and the production of iterations of proposals through critical enquiry by using diagrams, plans, elevations, sections, rendering, and modeling, all of which are informed by the initial program development (Hauberg, 2011: p 7). This technique is validated by the Royal Institute of British Architects Charter, which accepts that architecture itself is a method of research with the manifestation embodying research culminating in built form (Till, 2008: p 8).

The project in this study centers within an urban scale. Thus, a clear scope in which the design is defined should be developed. This process results in the development of a phased response, thereby breaking down opportunities for the realistic achievability of the implementation. The design response is situated within Phase 2 ("Adapt") and will be further discussed in Section 3.1. The processes undertaken include sketching, diagramming, collaging, detailed drawings, sections, perspectives, and constructional drawings. A 3D modeling relative to the Maldives is used as a visual representation for discussion purpose in Section 3.1 (Moosa et al., 2018).

3.3. Case study review

Should we fortify and hide behind ever-growing walls, retreat from the rising tides, or adapt and shape our cities into livable, responsive landscapes that engage and utilize the environmental context? These methods, particularly the latter (adaptation), have been considered through the lens of design to respond to climatic forces. For example, the concept of "aquatecture" was defined by Wylson (1986), in which water is utilized as a design element rather than an obstruction, and therefore incorporated into the design process. This research does not consider the three approaches of addressing RSLs of retreat, fortify, and adapt as mutually exclusive. Accordingly, this research explores a conjunction of all three methods to develop a holistic and resilient design response illustrated through a finalized set of images derived from an iterative design process. We reference existing studies for by Tam (2009) and The Intergovernmental Panel on Climate Change (2015) to understand and analyze the selected shortlisted case studies better. Then, we determine a set of key criteria.

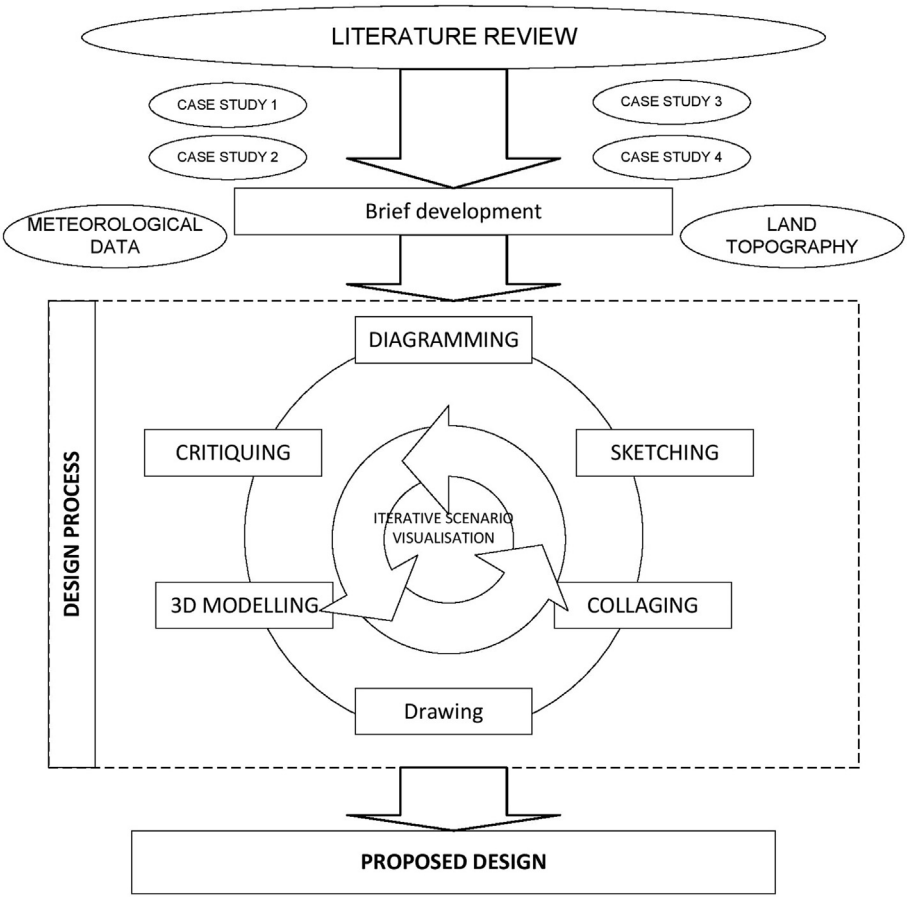

Fig. 4 Proposed framework (Author).

3.3.1. Analytical Hierarchy Process

During the literature review process, this research explored numerous examples that were excluded because of insufficient relevancy set against the research objectives. Any case study unlikely meets the required criterion for establishing a Maldivian model because of economic, cultural, geographical, and geopolitical differences. Notwithstanding this circumstance, the critical attributes of the selected case studies were determined through an analytical process. On this basis, we aim to identify key appropriate aspects and physical and strategic attributes for the potential implementation into the Maldives design model. We also provide a quantitative basis to determine the ranking of the factors analytically via a conventional multicriteria weighted matrix: Analytical Hierarchy Process (AHP).

The AHP supports multicriteria decision making (Saaty, 1959) allowing for a simultaneous comparison of multiple criteria (Brunelli, 2015). Moreover, AHP allows for quantitative (actual measurements) and qualitative (subjective opinions) pairing. The method uses *pairwise comparisons*, which consider simultaneous alternatives by atomizing a problem into its small components (Brunelli, 2015). Mathematically, the method is as follows: *pairwise comparison matrix*, $\mathbf{A} = (a_{ij})_{n\times n}$, with $a_{ij} > 0$, expressing the degree of preference of x_i to x_j. Saaty's theory indicates that each entry approximates the ratio between two weights $a_{ij} \approx w_i/w_j \ \forall i, j$. $\mathbf{A}$ can then be expressed in the following form: $\mathbf{A} = (w_i/w_j)_{n\times n}$. Considering multiplicative reciprocity $a_{ij} = 1/a_{ji} \ \forall i, j$, $\mathbf{A}$ can be further simplified and rewritten (Brunelli, 2015). We derive ratio scales from paired comparisons of criteria with allowance for minor inconsistencies through this method. Thus, the priorities (weightings) and consistency ratio can be calculated (Goepel, 2018).

The case studies presented in this research are analyzed according to nine (9) categories: *Cost, Term Solution, Efficacy, Social Acceptance, Ecological Impact, Maintenance, Social Equity, Speed of Implementation, and Scale*. The chosen case study applied distinct strategies to combat RSLs, including *Living Shorelines, Floodable Development, Primitive Floating Development, Modern Floating Development, and Coastal Armouring (Tetrapods)*. We seek to determine the viable solutions to find the "best-fit" for the implementation of the design model through the analysis of strategies against the abovementioned categories (Fig. 5).

In the pairwise comparison (Table 1), we have used Saaty's Balanced Scale (Saaty, 1980) with the corresponding verbal judgments proposed by Brunelli (2015).

Rankings are made by estimating a priority vector proposed by Saaty (1959) as the principal eigenvector of the $\mathbf{A}$ matrix. $\mathbf{Aw} = n\,\mathbf{w}$, where n and $\mathbf{w}$ are an *eigenvalue* and an *eigenvector* of $\mathbf{A}$. The normalized eigenvector of the matrix gives the ratio scale (weighting), and the eigenvalue

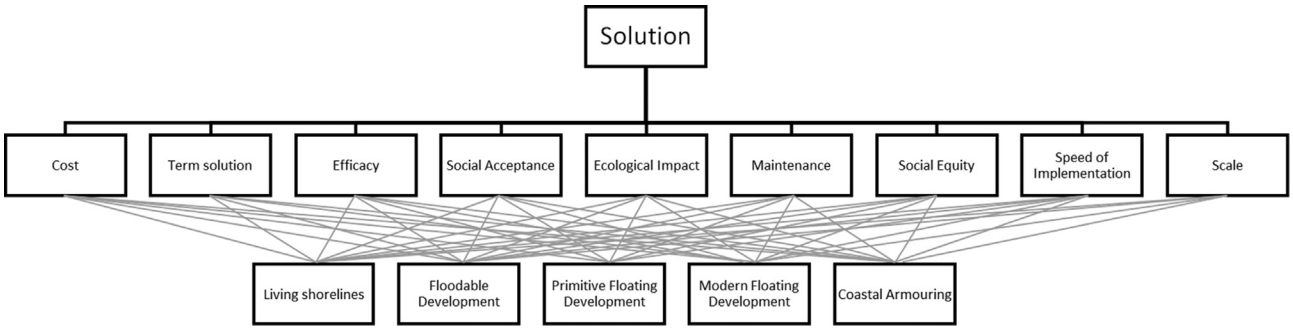

Fig. 5 Hierarchy of criteria and alternative solutions (Authors, 2020).

determines the consistency ratio (Brunelli, 2015). We undertake comparisons of 36 criteria and 10 solutions by using Goepel (2018) online software. The consistency ratio is determined to be CR = 3.5% for criteria and between 2.1 and −9.8% for solutions. This finding is deemed reliable next to a recommended value of <10% (Saaty, 1980). Equation (1) demonstrates that the priority vector for the criteria obtained is:

$$\mathbf{w} = \begin{pmatrix} 0.051 \\ 0.222 \\ 0.312 \\ 0.074 \\ 0.021 \\ 0.108 \\ 0.031 \\ 0.156 \\ 0.025 \end{pmatrix}. \quad (1)$$

Criteria ranking (Fig. 6) suggests that *Efficacy* and *Term Solution* are two significant benchmarks, and they cumulatively comprise >50% of the weighting.

We have selected the top five criteria and five solutions to construct a priority matrix. The top five criteria (presented in random order) include *Term Solution* (highest %), *Speed of Implementation* (highest %), *Maintenance* (lowest %), *Social Acceptance* (highest %), and *Efficacy* (highest %). The five solutions (selected in random order) for analysis are *Coastal Armouring (Tetrapods)*, *Modern Floating Development*, *Primitive Floating Development*, *Floodable Development*, and *Living Shorelines*. The obtained priority matrixes highlighted in Equation (2) for all solutions are shown as $\mathbf{A_s}$ and the criteria eigenvector $\mathbf{w_c}$. The final priority vector is $\mathbf{w_f}$.

Table 1 Balance scales and their association with verbal judgments.

Verbal description	Scale	Importance
Indifference	1	Equal
—	2	—
Moderate preference	3	Moderate
—	4	—
Strong preference	5	Strong
—	6	—
Very strong demonstrated preference	7	Very strong
—	8	—
Extreme preference	9	Extreme

The final ranking considering all the weighted criteria and solutions suggests that *Coastal Armouring (Tetrapods) and Living Shoreline* solutions are the two critical aspects in projects combating RSLs, together comprising >50% of the weighting (Fig. 7). However, not all environments provide physical conditions that are suitable to the above-mentioned solutions. The third highest ranked solution is *Modern Floating Development*. A hybrid solution triangulates among the top three solutions where possible and appropriate.

3.3.2. Case study 1: sea change Boston

The Sea Change Boston (SCB) project by Sasaki Associates is of particular relevance to the Maldives. The project is unique because it considers RSLs and tidal- and storm-related flooding in Boston, Massachusetts. It also features an in-depth analysis of cause and effect, specifically in the

$$\mathbf{A_s} = \begin{pmatrix} 0.125 & 0.220 & 0.123 & 0.409 & 0.550 \\ 0.437 & 0.044 & 0.033 & 0.045 & 0.078 \\ 0.047 & 0.222 & 0.132 & 0.071 & 0.064 \\ 0.066 & 0.231 & 0.356 & 0.169 & 0.074 \\ 0.326 & 0.283 & 0.356 & 0.306 & 0.234 \end{pmatrix}; \quad \mathbf{w_c} = \begin{pmatrix} 0.222 \\ 0.156 \\ 0.051 \\ 0.108 \\ 0.312 \end{pmatrix}; \quad \mathbf{w_f} = \begin{pmatrix} 0.284 \\ 0.135 \\ 0.079 \\ 0.110 \\ 0.241 \end{pmatrix} \quad (2)$$

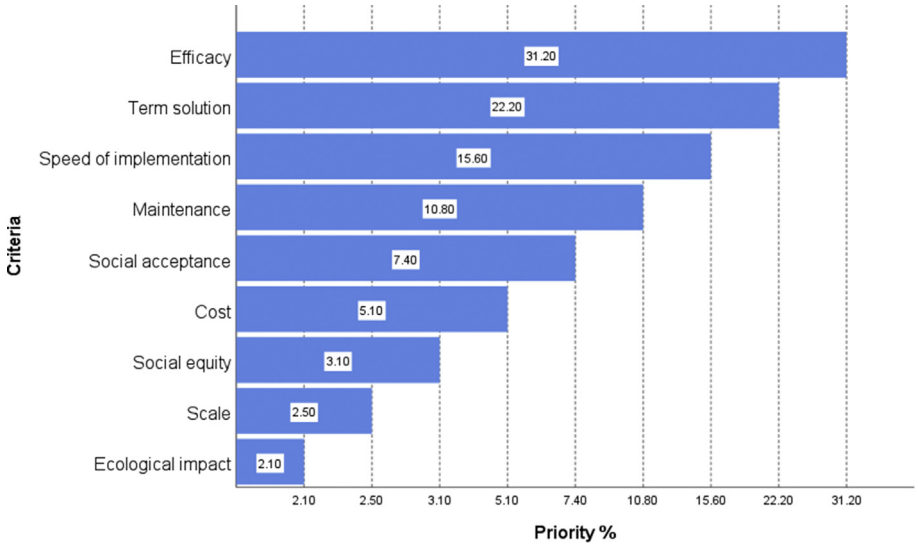

Fig. 6 Priority ranking of criteria (Authors, 2020).

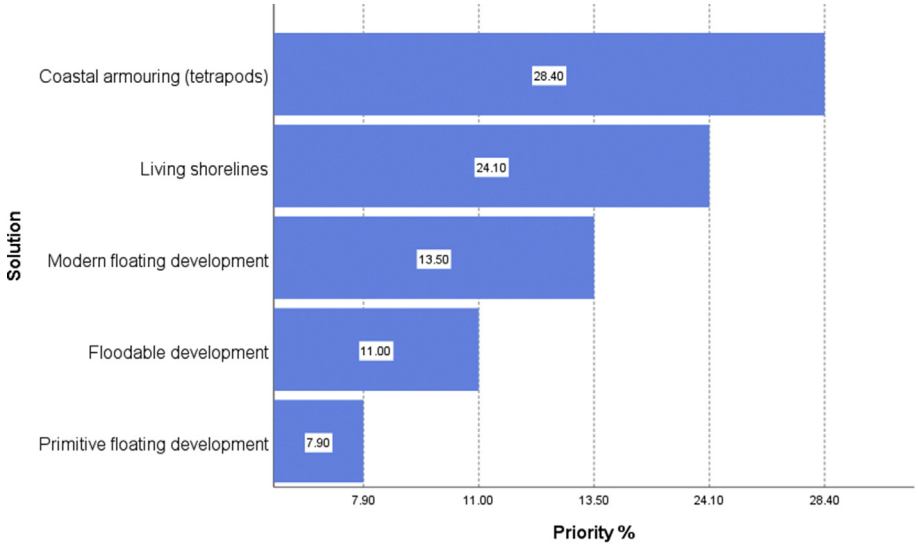

Fig. 7 Priority ranking of solutions.

way that mitigation methods are considered. The SCB project was implemented on a large scale (incorporating government-level initiatives), which proved particularly relevant to this research. The design proposal of the project (Fig. 8) considers the diversity of risks and factors associated with increased flooding in Boston due to RSLs and other flooding scenarios. The proposal outlines a number of sustainable long-term strategies to minimize and avert the devastating effects of water action against the city. A scenario analysis for RSLs and flooding events and diverse design schemes and implementation strategies are considered. Sasaki Associates provide in-depth analyses that outline response mechanisms to given scenarios.

The SCB is comprehensive in its stakeholder engagement and "buy-in" strategy, thereby establishing confidence, understanding, and acceptance through community education and engagement with the regional government to provide an overview and continuity of dialogue on resilience planning for Greater Boston. A "call-to-action" exhibition showcased the findings derived by a consortium of global experts consulting in climate, engineering, academia, advocacy, and politics, and who were involved as a steering committee on the project (Sasaki Associates, 2014). Testing such design proposals at a small scale and providing "as-built" data, which can be applied in small at-risk communities, are critical for dialogue, planning, and delivering on design. This approach ensures that the momentum for action is maintained, and good solutions are shared with the rest of society. However, patenting and exploiting global markets is not conducive at present.

3.3.3. Case study 2: MOSE, Venice

The MOSE (2017) project aims to defend against flooding in Venice, Italy through fortification. Here, a mechanized wall is enacted using hydraulic pumps as high tide approaches. Once inclined, these pumps create a separation between

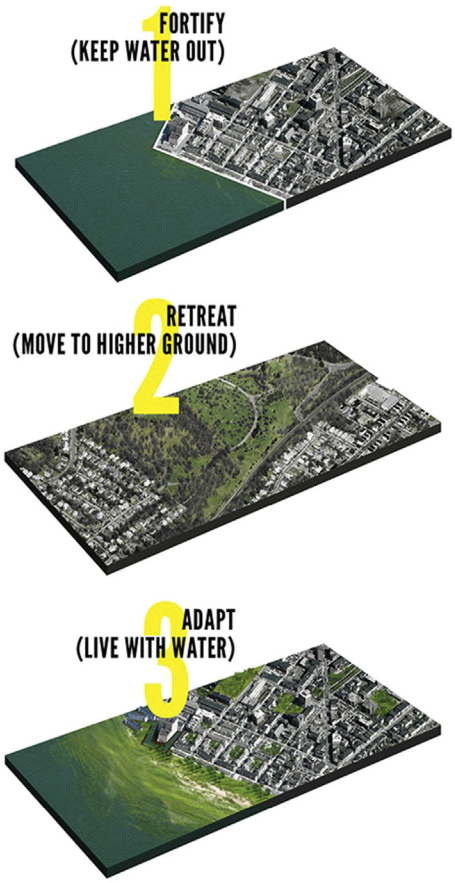

Fig. 8 Options for climate change reactions (Sasaki Associates, 2014).

the Venetian Lagoon and the Adriatic Sea. The MOSE project is a good example of how technological advancements have allowed for developing innovative methods of "fortification" (e.g., underwater seawalls), despite remaining short-term in nature. In this project, Venice provides another example of a "small island nation" with fortification issues. However, unlike Malé, Venice has Italy as a "fallback" for migration and decanting large populations. Notwithstanding this situation, strong correlations to the Maldives exist in this example given the need of both locations for preservation because of historical and cultural significance.

Infrastructure comprises 78 hydraulic gates that are automatically programmed to rise when tidal waves reach a minimum specified height (Water Technology, 2014). Once raised, tidal flow is restricted from inflowing to the lagoon (Fig. 9).

The project contains other defensive mechanisms to combat RSLs, including reinforcing and raising coastal boundaries where possible (quaysides and paving levels). Although MOSE is considered a short-to medium-term solution and does not fall within the scope of the aims of this research, it demonstrates a diverse-option approach to ameliorating immediate effects, including the implementation of mechanisms, technologies, and structural infrastructure. Notwithstanding the temporary nature of these solutions, these methods can inform and feature as components to permanent solutions in this research. The MOSE project already provides Venice a crucial delay in the "critical path" toward the catastrophic effects of RSLs and tidal activity. However, capitalizing on this precious extension of time can ensure that a feasible and sustained strategy is concurrently implemented during this "float" period, which is of even great importance to the future of the city.

3.3.4. Case study 3: floating city project

The Seasteading Institute (The Seasteading Institute, 2014) commissioned DeltaSync to design a permanent ("seasteading") floating city, which is largely a self-governing, sea-dwelling municipality (Fig. 10). The Institute negotiated with nations willing to host such a project and provide transparent and politically independent governance thereafter (DeltaSync, 2013). Development was founded on expansion from existing delta-located cities and further increased and offered cost-effective, practical, and market-feasible permanent "aquatecture" over a period (Wylson, 1986). The political and economic framework of the Seasteading Institute seeks to create an "independent society" with contemporary laws and governance that has no relationship to outdated governmental structures that emanated in bygone centuries.

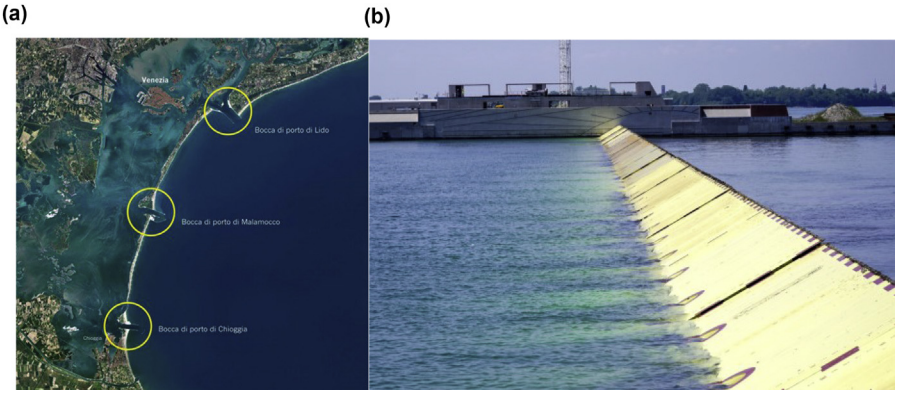

Fig. 9 (a) macrogeographical alignment and positioning; (b) close up of MOSE (2017) project, operational defensive wall.

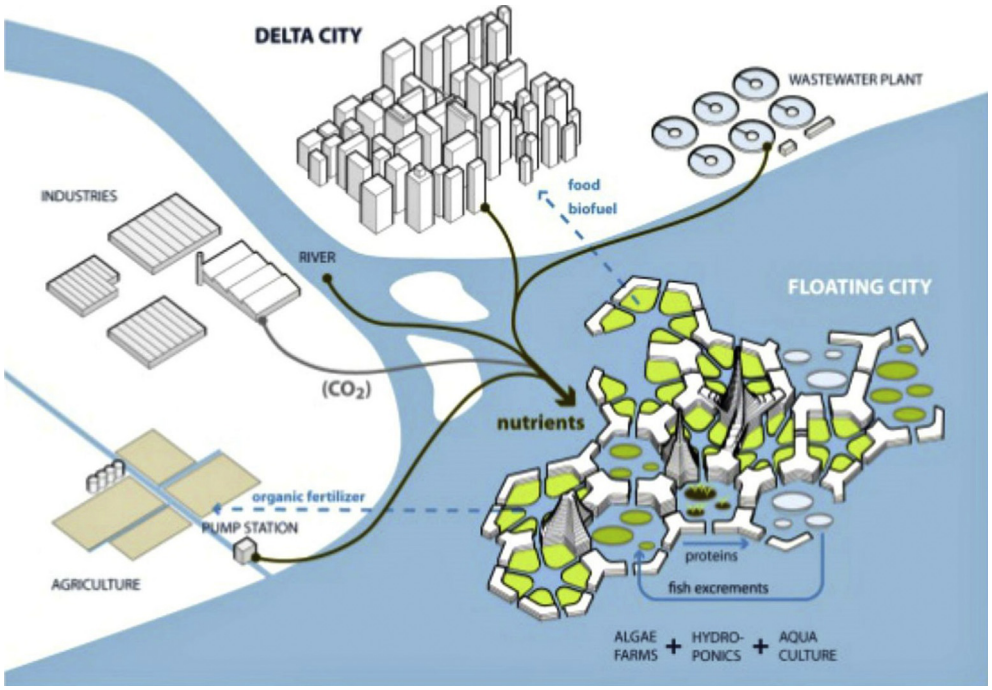

Fig. 10 Floating city concept (DeltaSync, 2013).

The proposal, as a permanent and sustainable solution, aligns with the objectives of this research to provide an adaptive sanctuary migration and habitation for populations threatened by RSLs. The scheme is scalable and invites expansion and concerns itself with providing respite to the needs of exponential increases in population and pressure on pastoral lands for food. This scheme is self-sustaining and independent and offers a feasible option for consideration in the Maldives.

3.3.5. Case study 4: floating houses in IJburg

Amsterdam, the capital of the Netherlands, comprises many neighborhoods composed entirely of floating dwellings. IJburg, a residential area within Amsterdam, currently accommodates 45,000 people (Fig. 11). Here, houses designed by Dutch architect Marlies Rohmer (2011a) are not constrained by a typical "grounding" but float on the water surface, thereby providing natural vertical shifts and gentle changes in tidal activity and RSLs. Correspondingly, the design rationale and primary aim of the designers and municipality is to form defensive and adaptive relationships with water.

Fig. 11 Floating houses in IJburg (Rohmer, 2011).

Given that approximately one-third of the Netherlands sits below sea level and, although similar to the Maldives, it experiences increasing pressure from RSLs, its people have been attuned to living with water for centuries (Rohmer, 2011b). With what are now similar circumstances, this case study provides a relatable option to areas, such as the Maldives, because the atoll—lagoon structure of the islands provides similar sheltered conditions to support comparable adaptive architecture.

3.3.6. Case study 5: district 4, Vietnam

Shaw (2006: p 525) mentioned that "most of the disasters in Vietnam are related to the weather conditions and climate change." In recent years, climate change has exacerbated the intensity of seasonal flooding, to which Vietnam has responded by implementing the Ho Chi Minh City Climate Adaptation Strategy. This plan fits within the Vietnam Climate Adaptation Partnership and involves collaboration with Dutch engineering company Witteveen + Bos, which specializes in flood risk management and urban development. The partnership between Vietnam and the Netherlands aims to implement an adaptive climate change strategy for Ho Chi Minh City by focusing on "urban development and climate adaptation" (Davies, 2015: para. 5). The adaptive approach here is to develop a series of reservoirs throughout the districts that intend to mitigate RSLs and tidal activity in flood-prone areas. This approach is set to be used as an adaptive template for expansion to other flood-prone districts, such as Phnom Penh.

Notwithstanding this concept, the political aspects associated with such development beg consideration. The villages in Ho Chi Minh City have infrastructure and architectural built form (Fig. 12) that account for and are already adapted to mitigate RSLs and tidal activity in this flood-prone area of the world.

Fig. 12 Improvised delta housing along Khanh Hoi Canal, District 4 in Ho Chi Minh City (Davies, 2015).

The effects of RSLs are likely to become prominent once the villages are moved out of the delta area and replaced by planned commercial expansion. The adaptive nature of civilizations here and elsewhere (e.g., the semi-nomadic Penan people indigenous to Sarawak) favor resilience to RSLs through elevated and semipermanent structures. This concept does not suggest that such cultures do not face other cultural, geopolitical, and environmental (as a small sampling) pressures. However, these structures lack the permanency of modern construction. Meanwhile, the agility of modest and lightweight structures facilitate adaptability to the site and its constraints, climatic conditions, and fluctuations in water levels, especially at a time when the villagers were economically and geographically pressured to locate along the canals.

Overall, the relevance of this project derives in its use of sound design principles, which have been applied out of necessity and in response to the vernacular conditions of Vietnam. This notion suggests an intolerance of modern design and infrastructure to be flexible to changing conditions due in part to architectural permanency and choice of materiality.

4. Findings and discussion

This research identifies and reviews potential case study candidates well beyond those presented in this paper. The four examples selected are merely representative of the increasing body of work in this area and together highlight the diversity of circumstance, location, culture, and varying degrees of familiarity related to living with water as critical elements to habitation and survival.

The strategies applied as singular factors or components of a system approach are further examined. The purpose of conducting such analysis is to understand some non-hypothetical (design-only) options and strategies available better, given that built examples have been demonstrated in response to the varying methods of defense and adaptivity of RSLs within diverse contexts. In light of the specific and unique circumstances, design must work with and engage all stakeholders who must be part of the discussion and process to ensure community adoption and acceptance. This situation draws a critical thread to the circumstances in the Maldives, and, in turn, efficiently informs the aspirational design brief of this research, particularly relating to which strategy best serves the immediacy of tidal flooding and RSLs on the island: (1) fortify (defend against water by keeping it out), (2) retreat and isolate (move further inland or to higher ground, if available), or (3) adapt (live with water as a "new normal" either by working with it—shaping to control it—or circumventing its processes to an alternative way of living) (Sasaki Associates, 2014). Similarly, this situation has been occurring in the Netherlands for centuries.

Although a short-term solution, fortification through defensive barricades has been adopted in most of the case studies examined. This approach is likely favored because it is less disruptive to societies within this context, meaning that the daily rhythms of life remain unchanged to a great degree. The industry and most other sectors can continue to support the economy, and the culture and heritage of a local remain intact. However, this solution is not sustainable and does not suit large contexts with extensive coastlines to defend. The RSLs can strike at the heart of the MOSE project in Venice (Case Study 3). Accordingly, no mechanical system is infallible to malfunction. Although this solution may offset the effects of ingress in the Venetian context, it is inappropriate for the Maldives. This strategy requires land on either side to ensure that intervention, when raised, "bridges" the gap like a dam wall. Nevertheless, this concept can be considered as part of a sequence of phased defensive interventions but not on the critical path to a sustainable solution in its own right.

Nomadic communities and indigenous peoples that reside in coastal areas have what appears to be a natural relationship with water. Communities resettle after disasters to less affected areas or islands by using "retreat and isolate" options, rather than setting permanent structures to territorialize the ownership of land against nomadic seasonal migrations (as the early people of the Maldives did) (Naylor, 2015: p 733). This nomadic tradition of the Maldivian people (now considered primitive) has since ceased because it is no longer feasible within a contemporary urban framework. Even if continued, the Maldives, with a projected RSL of 2 m, would be submerged due to averaging 1.6 m elevation above sea level (Jevrejeva et al., 2016).

However, adaptation considers water as a key design parameter and an accepted element central to decision making, which can co-generate positive outcomes through

design. For example, Rotterdam in the Netherlands has urban master plan schemes with designated flood precincts. Here, the strategy is to deliver resilient urban design infrastructure through a "systems" approach with principles intended to meet the current and future needs of the entire districts dedicated to living with water (van Veelan, 2016: p 24).

The process of implementing adaptation on a societal scale is initialized at an institutional level. Thus, entire societies must adapt education and act as the agents for change. Engaging the tutelage of future generations to form and consolidate changing views and practices allows for developing sustainable societies; hence, "institutions themselves may need to be restructured" (Kane and Yohe, 2000: p 2) for evolution to occur. However, active education through stakeholder engagement also proves to be critical because of the imminency of the problem. Manin, Stein, and Mansbridge (1987: p 352) held that "a legitimate decision does not represent the *will* of all, but is one that results from the *deliberation of all*". Communities must be given the opportunity to contribute and have their concerns and voices heard to ensure successful implementation of such extensive and sweeping changes.

The current infrastructure of Maldivian living demonstrates that the country is dependent on external sources for most of its resources. According to the National Bureau of Statistics (2018), almost all of its staples are imported, with local fisheries being the major source of locally sustained food. The UN's Food and Agriculture Organization (Food and Agriculture Organization, 2008) indicated that the Maldives produces less than one-tenth of its overall food requirements. Malnutrition, anemia, and vitamin A deficiency remain prevalent among the population due to the lack of food security policy and nutrient-rich local produce.

Consequently, other sectors of Maldivian infrastructure also lack in terms of self-management and sufficiency. With regard to energy production, lack of renewable sources (e.g., solar, wave, and wind) being used but heavy reliance on the burning of fossil fuels for power generation is observed (National Bureau of Statistics, 2018). Moosa, Jonescu, Sutrisna, Hammad, and Do (2018) highlighted

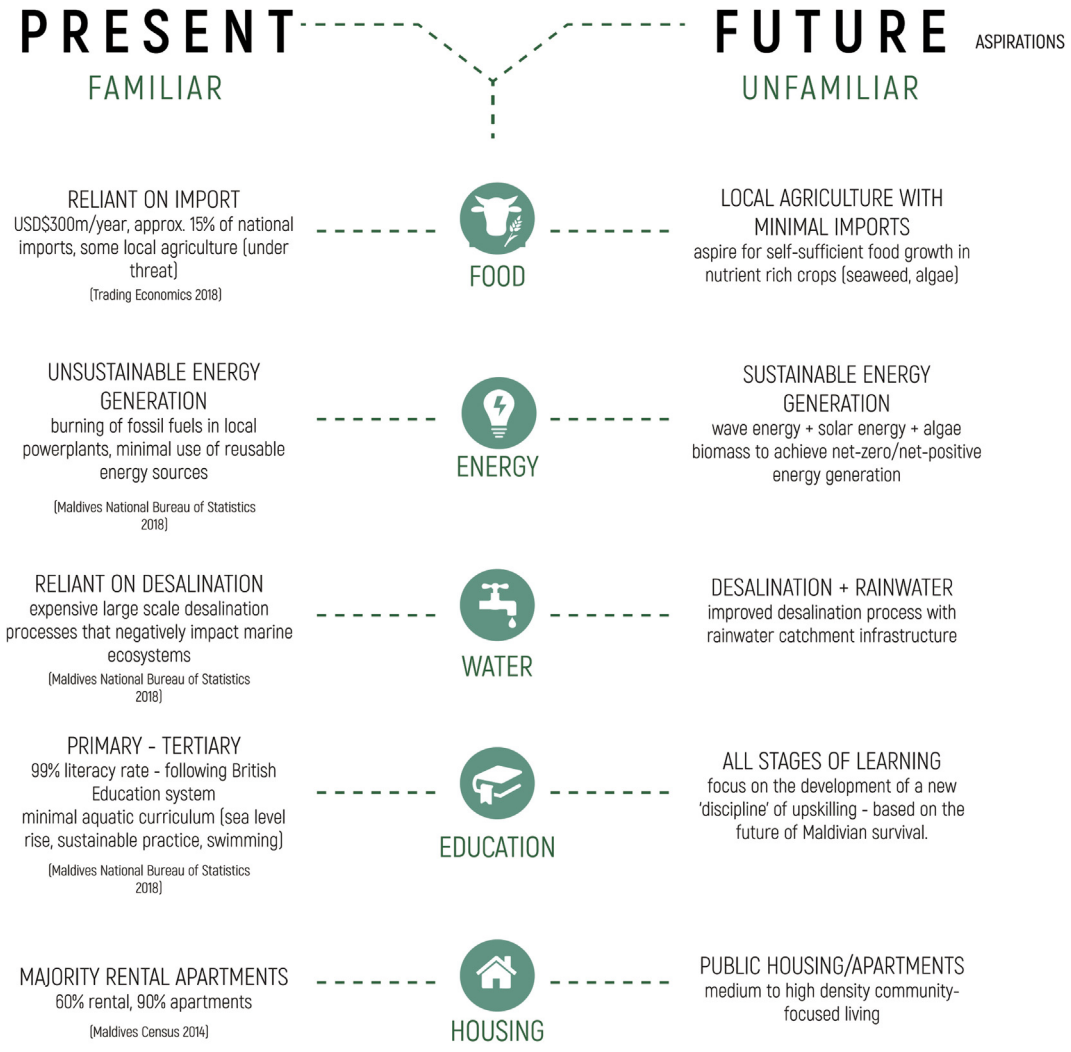

Fig. 13 Present situation in the Maldives, including the required changes in sociopolitical and cultural circumstances (Author).

that Maldivians are dependent on extensive desalination processes to provide sufficient potable water. However, the current practices are costly and negatively affect marine ecosystems through their operating processes. Finally, the current education system of the nation must incorporate a unique curriculum that highlights the current issues and methods for mitigating and adapting in the future (Fig. 13).

We apply viable "best-fit" solutions for the implementation of the design model and design decision-making on the basis of AHP ranking that considers categories (*Cost, Term Solution, Efficacy, Social Acceptance, Ecological Impact, Maintenance, Social Equity, Speed of Implementation, and Scale*) and strategies (*Living Shorelines, Floodable Development, Primitive Floating Development, Modern Floating Development, and Coastal Armouring [Tetrapods]*) to combat RSLs (discussed in Research Methodology).

4.1. Design outcome

This study explores opportunities for building resilient infrastructures by using an iterative design approach. The primary solution sought adapts to RSLs in the Maldives through the disciplines of architecture and construction management. The proposed infrastructure sits within an urban scale. Hence, a clear scope in which the design is defined must be developed. This process results in the development of a phased response involving breaking down opportunities for realistic and achievable implementation. The five phases are outlined in Fig. 14 with Phase 2 ("Adapt") being a primary focus for this research.

The criteria driving the iterative design process are derived from the bricolage of research, including the case studies, which support decision making relative to the objectives of this paper. This proposal seeks to initiate and stimulate conversation about taking ownership of what is undoubtedly a complex and critical situation. Such concept presents itself as a method for enabling the Maldives to develop self-sufficient practices and resilient urban growth proactively in the face of rising seas. Although this proposal does not offer a panacea solution, the architectural design aims to identify the Maldives as a prototype for future coastal growth. The design timeline of the phased response suggests "Module 01" to be implemented in the year 2035 to initiate resilient living in the Maldives formally.

This method allows for the use of the existing extensive infrastructure and amenities of the city (e.g., medicine and education) and exposure to the mass population by locating the structure off the coast of Malé. The incorporation of this method into the current city aims to commence the process of social acceptance and change even through visual connection. The indicative location (Fig. 15) was chosen because it is:

1. Within the protected waters of Kaafu Atoll,
2. Positioned on an elevated reef flat,
3. Nondisruptive to current ferry routes,
4. Close to a public beach area in Malé (to increase visual interaction).

The typological exploration considers elements of the urban framework necessary for communities and cities to grow and flourish (Popovic et al., 1995). These elements include (but are not limited to) residential factors, education, agriculture, water, medicine, commercial and civic factors, and energy. The elements are grouped into "urban scenarios" (or typologies) through a process of drawing connections between community needs and infrastructural requirements and determining how the process can be translated into a "landless," self-sufficient, and resilient

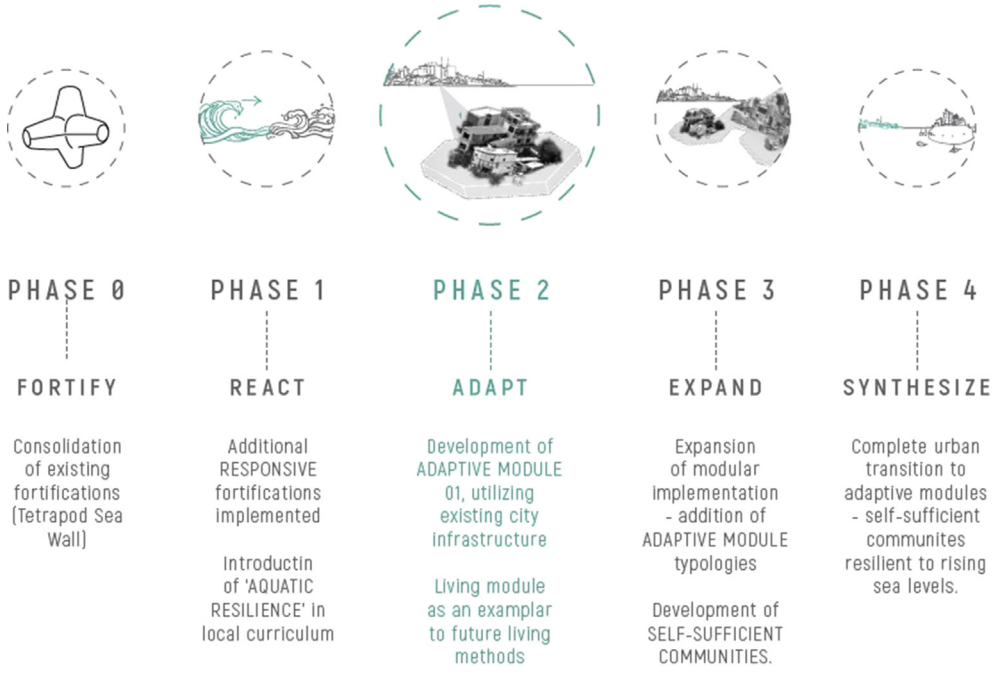

Fig. 14 Potential phase responses with Phase 2 considered appropriate for the design research approach in this paper (Authors).

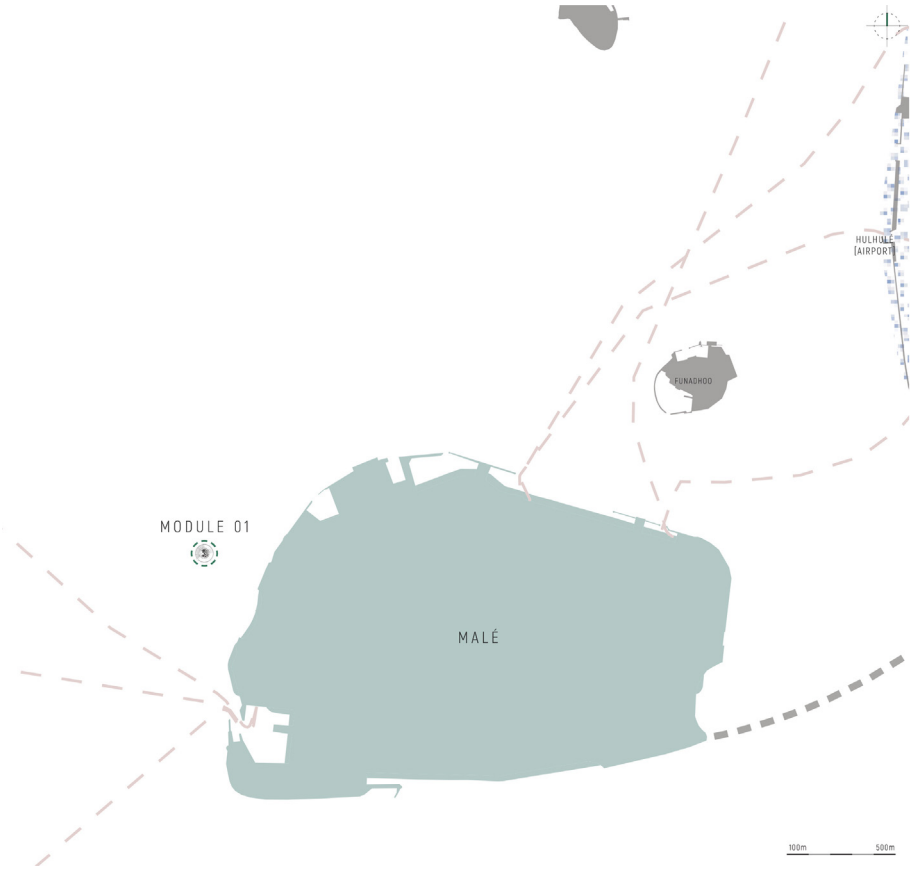

Fig. 15 The first module (Phase 2) is of an urban scale and typology; the first module acts as a gateway for future development, becoming a transition point between current and future life (Authors).

built form (i.e., an appropriate typology for Module 01). This adaptive and resilient response should deliver the following high-level aspirational outcomes derived from Moosa (2018):

1. Adaptability: The design must consider how it supports existing Maldivian society and allows for population growth. It must be modular, thus facilitating ease of construction and repetition and making it adaptable, scalable, and cost-effective to replicate as demand increases in future phases. The infrastructure must be flexible and offer multi-use functionality to rationalize spatial requirements and allow for potential expansion (of Malé) through further modular components rather than land reclamation. Further addition of infrastructure modules may require complete shifts from existing islands or formations of new islands.
2. Resilience: The design should be adaptive to the changing climatic conditions, specifically RSLs, tidal action, and storm surges. The idea of what forms "resilient" responses is examined by exploring "aquatic architecture" typologies and assessing case studies. This concept highlights that the Netherlands has worked with water for centuries, accepting its presence and controlling its path and effect by designing with water as a key criterion. Here, resilience is equated to the successful management of function relative to water.
3. Phased process: The proposal is part of a phasing-in process. This notion is suggested to ensure that the modular implementation meets the current and growing needs of the Maldivian population. The modular nature of the design proposal is also intended to allow for a projected implementation strategy. The design approach needs to consider this long-term phasing and resilience strategy because of the imminent nature of RSLs in the Maldives. However, this approach greatly depends on the sufficient provision of time purchased through certain short-term defensive methods.

The initial implementation of a multi-use community infrastructure enables the local community to transition into an alternate mode of living. Therefore, the initial modular *island* is designed as a "template" for use in further future development. This community development includes (1) a community hub (public domain), (2) residential apartments (similar to existing residential typologies found in Malé), and (3) trade of goods and services for economic, provisional, and employment needs (e.g., business, food, basic health care, and enterprise).

The infrastructure proposes to commence and support a phased community migration from Malé toward offshore development and is considered part of its current urban framework—one with demand-driven capacity to expand, in keeping with the effects of RSLs and self-sufficiency.

Local crop production is considered critical to a sense of community self-sufficiency (Fig. 16a—c) and includes production of leafy greens, small fruits, vegetables, and root vegetable crops (Barth, 2018). Although this production is not intended to suggest an ability to meet diverse dietary needs, it is a physical manifestation of the need to be adaptive and explore alternative means of deriving sustenance. The other harvestable crops suggested in the proposal include scallops, mussels, oysters, and other crustaceans, seaweed, and algae; atmospheric CO_2 must also be mitigated (Smith, 2011).

The Maldives should develop self-sufficient communities with residential, educational, and medical facilities and provisional and energy generation, which have each been considered and adopted into the design proposition.

Like Dutch architects who have, for some time, increasingly shifted toward floating homes in Holland (Palca, 2008: para. 2), the concept is bedded to the sea floor through a drill pipe core and further anchored through a 3D-printed artificial reef (Fig. 17a—c). A Modular Artificial Reef Structure already implemented in the area (Goad, 2014) further enhances the immediate marine ecosystems. The design incorporates other critical design considerations, such as an educational research laboratory, and an outer-ring, multipurpose defensive buoy system, thereby minimizing the wave impact and creating a calm-

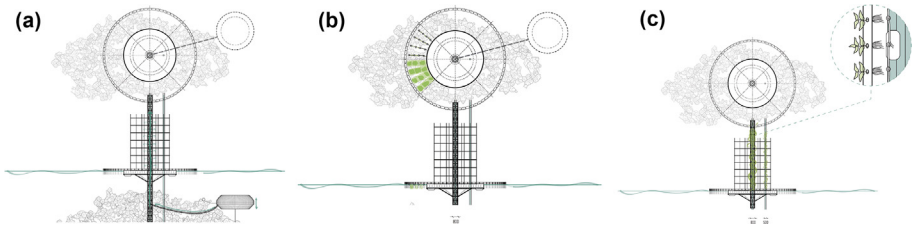

Fig. 16 a—c: (left to right): (a) CETO desalination buoy treats water through self-harnessing wave energy; (b) aeroponics and algae harvesting for biofuel; (c) aeroponic crops and reticulation (Author).

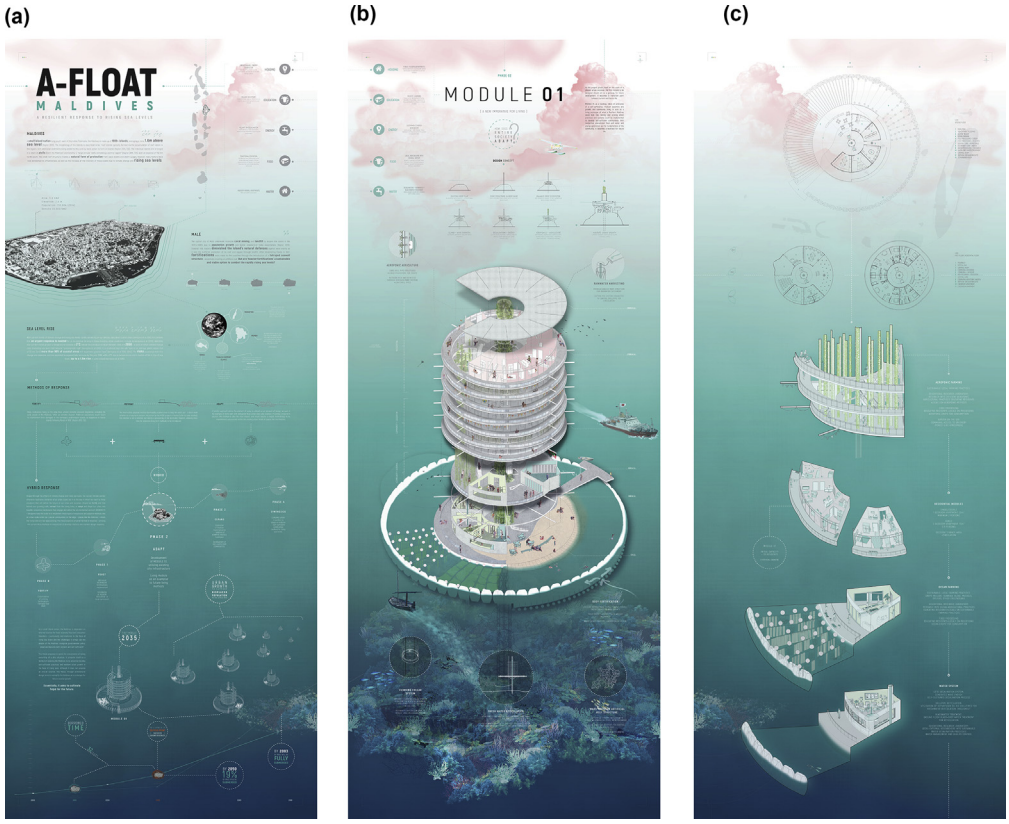

Fig. 17 (a) Phase 2 anchoring system and scalable pods; (b) "Module 01" conceptual design model showing the central core, urban-scale harvesting and research, and the gateway to future development; (c) "Module 01" (Phase 2) urban-scale aquatic farming and varying spatial arrangements for habitation (Authors).

water lagoon for aqua-farming and community interaction. The system also allows for wave-energy harvesting and facilitates a "climbing collar system" sleeve, rainwater harvesting, aeroponic agriculture, and expandable water desalination. Black and grey water treatment and reticulation infrastructure also feature in the design.

Similar to this concept, the project design incorporates a central "climbing collar system" sleeve to accommodate ongoing RSLs and tides (Crane and Rigging, 2015), thereby allowing for inherent and natural vertical rise and fall of the structure that is further supported by its own buoyancy. As with Holland's floating homes, government buy-in and commitment are also required. Palca (2008) (para. 2) suggested:

> The inevitable rise in sea level that comes with climate change is going to make it increasingly difficult to control flooding in low-lying Holland. But instead of cursing their fate, architects are designing a new Holland that will float on water, and the Dutch government seems willing to try out the scheme. Holland has made other countries begin to question, too. Who says you have to live on dry land?

To this end, this proposal seeks to highlight a call to action and collaboration from the disciplines of design, engineering and infrastructure construction, specialist aquatic consultants, and the government. This research and future initiatives will exponentially intensify discussion and advocacy given the urgency in the Maldives and in many other low-lying areas worldwide. Moreover, this research also demonstrates the willingness to challenge complex issues. It also offers the architectural design conceptualization of some complementary options that exist as disparate systems. The collective contribution of scholars suggests alternative means by which one may create the beginning of a semi-aquatic living paradigm in vulnerable areas under imminent pressure to adapt to permanent climate-induced RSLs.

5. Limitations

Given that the design is formulated on what has been dubbed as worst-case scenario RSL trends, it is situated in the year 2035 when sea levels are projected to rise by 350 mm but crafted to withstand a theoretical rise of 2000 mm by 2100. Defense methods, including buoy fortifications circumventing the design, allow for protection from extraordinary wave events and rough seas. Given these different levels of climate effect and existing climate adaptation policies, the available building technologies in each study area may lead to different responsive solutions. The effect of individual projects upon implementation in certain case studies should be reviewed, similar to a post-occupancy evaluation, to ascertain their efficacy for addressing climate change in practice.

A cost—benefit feasibility analysis of any case study is required to determine the viability of a prior to proceeding; yet, this is beyond the scope of this paper, which proposes a theoretical design response as a feasible architectural and infrastructural typology. Moreover, quantification next to, in particular, various environmental, economic, living, and sociocultural aspects will be difficult. If such a project is deemed feasible and undertaken, a post-construction, as-built occupancy analysis will provide a physical and functioning exemplar on which further analysis and research can be conducted for future application. As with any research by design, documentation continues to evolve because the work is further refined and tested at scale, modeled, and retested.

6. Conclusion and further research

Climate change undoubtedly appears as one of the significant junctures of our time. The United Nations Development Programme, 2017 "2030 Agenda for Sustainable Development" acknowledges this situation through its "Climate Action" mandate, which defines critical "resilience and adaptive" goals. The research highlights the potential effect of RSLs in low-lying countries, such as the Maldives, and this issue on a global scale by using multiple case studies. This study positions research on RSLs and climate change in the Maldives through the scope of architecture and construction management, given the propensity of these disciplines' inclination to advance and cater to the needs of global populations. In particular, this study considers the global and societal scale of impending devastation that low-lying coastal areas will likely continue to experience, thereby driving the critical need for such research and discourse. Maldivians face significant challenges not only to daily living and the total destruction of the country but also to the endurance of their national culture.

This research aligns itself to real-world deliverable outcomes through case studies. Moreover, it proposes a theoretical architecture and infrastructure typology addressing critical components required to provide habitus for communities at risk of becoming fully submerged. Instead, the island must consider a scalable offshore typology that initially forms part of its infrastructure. This proposal's composition and deliverability of such a framework have been considered and applied in a learned way even though it is theoretical in nature. The typology has been conceived through a bricolage of research and an iterative design process as critical methodologies. The case studies highlight the diversity of contexts to which RSL concerns relate, including their varying undertakings to mitigate their short- and long-term effects. Specifically, international exemplars with longstanding and existing adaptive relationships with water and associated "aquatic architecture" exist to understand scalable options better amid RSLs. Therefore, testing the limits and possibilities of architectural implementation under such extreme circumstances is subject to lived and highly developed examples.

The iterative process is distilled and refined into a number of images intended to address the critical components required of a functioning community for the purpose of this paper. These initiatives are presented in an adaptive "Phase 2" response scenario. Accordingly, these efforts seek to agitate the academic, governmental, and industrial communities further to debate, discuss, and collaborate toward the implementation of real "built" initiatives and propositions for the Maldives.

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