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Managed retreat as a response to natural hazard risk

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Managed retreat is a potentially important climate change adaptation option, providing an alternative to structural protection or accommodation measures to manage natural hazard risk. However, its application faces challenges given the projected scale of climate-induced displacement and the difficulties of resettlement. We evaluate the drivers, barriers and outcomes of 27 recent cases of managed retreat that have resettled approximately 1.3 million people. A conceptual model based on two key factors—who benefits from retreat and who initiates it—organizes the diverse set of cases into four quadrants. Different sociopolitical dimensions emerge as particularly influential in each quadrant. The model establishes a foundation for understanding and anticipating case-specific complexities. It can be used to unpack the landscape of managed retreat and evaluate its potential future applications.

Changing climatic hazards are already driving migration and community relocation globally, and by 2100, sea level rise alone threatens to displace 72–187 million people[1]. Risk management approaches are needed to support the millions of people exposed to potential displacement. Accommodating such risks has limits, and structural protective measures (for example, levees) involve high maintenance costs, environmental damage, and increased development in hazardous locations[2,3].

One alternative is managed retreat, the strategic relocation of structures or abandonment of land to manage natural hazard risk. Often considered transformational adaptation, managed retreat brings its own set of challenges, whether political, social, or legal. It has yet to be widely analysed or adopted; still, examples are beginning to accumulate[4].

We document, analyse, and compare 27 past and ongoing efforts to implement managed retreat across the globe. This is the first study to synthesize a wide-ranging set of empirical evidence on managed retreat. Over the past three decades, approximately 1.3 million people have relocated through managed retreat (Supplementary Table 1), which pales in comparison to this century's projected displacements.

We develop a conceptual model representing core interactions across the comprehensive data set as a foundation for understanding recent and future applications of managed retreat. The model identifies key sociopolitical attributes likely to promote or impede adoption of managed retreat. Across diverse settings, it can assist researchers and practitioners evaluating if and how to implement managed retreat. Overall, our approach complements physical-science and economics methods in supporting management of natural hazard risk in a changing climate.

Challenges implementing managed retreat

Although applications of managed retreat vary widely, existing studies have focused on only one or a few cases at a time. These studies provide limited cross-cutting insight about the use of managed retreat as a risk management strategy. Further, global coastal-adaptation models generally omit retreat and focus only on structural protective measures, or they use economic efficiency rules to differentiate between protection and retreat[4,5]. By contrast, our study integrates across all available cases in the literature and examines social, political and economic influences.

Retreat has long been acknowledged as an alternative to coastal protection, appearing as such in the IPCC's First Assessment Report in 1990 (ref. 6). 'Retreat' is used to capture the philosophy of moving away from the coast rather than fortifying in place[4]. 'Managed retreat,' on the other hand, derives from coastal engineering and has been defined as 'the application of coastal zone management and mitigation tools designed to move existing and planned development out of the path of eroding coastlines and coastal hazards'[7]. The term has also been used to describe the landward relocation of riverine flood defence structures[8,9]. We identify two defining features of managed retreat in coastal and other settings. First, it is a deliberate intervention intended to manage natural hazard risk, requiring an implementing or enabling party. Second, it involves the abandonment of land or relocation of assets. We use those characteristics to define managed retreat as the strategic relocation of structures or abandonment of land to manage natural hazard risk.

Managed retreat has been used only in limited fashion to date. Past work has identified a number of reasons why its usage has been relatively scarce, despite potential economic and broader benefits.

First, managed retreat is often controversial because of the social and psychological difficulties in displacing people from their homes, 'the central reference point of the human existence'[10,11]. Other social and emotional attributes, such as attachment to place, perceptions of the potential destination, and economic prospects, also shape attitudes toward retreat[12]. Managed retreat is not a low-regrets option, nor is it easily reversed. Intangible costs, such as cultural-heritage loss, can be particularly high with retreat, and decision-makers may shy away from the potential political contention[8,13].

Another key obstacle is the 'levee effect' feedback loop: once structural protection is built, development tends to increase behind it, amplifying motivation for its continuation[14]. In Australia and the US, local governments have encountered legal challenges when trying to cease maintenance of defences[15,16]. Without adequate foresight, incremental protection measures may decrease the feasibility of subsequent retreat[3].

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Managed retreat is spatially and economically different from many other risk management measures. The benefits of protection and accommodation measures largely accrue where they are implemented, whereas retreat in one location can benefit other linked, exposed areas, such as in the Netherlands (Supplementary Table 2, Example 6)[17]. Unlike engineering measures with ongoing maintenance costs, retreat once implemented involves minimal recurring financial costs while permanently reducing natural hazard risk. The timescale and discount rates used in cost–benefit analysis therefore affect the ranking of coastal management measures; one study found that retreat tends to be favoured over timescales greater than 25 years[18].

Documenting recent experiences with managed retreat

To compile a comprehensive database of recent efforts to implement managed retreat, we searched for 'managed retreat,' 'community relocation,' 'climate displacement,' 'island abandonment,' and 'planned resettlement' in the peer-reviewed literature and in reports from governments, development agencies, and research organizations. Our definition of managed retreat (see Methods) excludes resettlement driven by mining, dams, or general development objectives. The definition also requires at least two parties, an implementing or enabling party and the residents affected by the intervention because they are relocating or because their assets are moved or altered in land abandonment. We include any instance in which one party initiates retreat, regardless of whether retreat has taken place. Only sufficiently documented examples could be analysed, so smaller-scale and developing country examples especially may have been missed.

The 27 cases identified, described in Supplementary Table 2, capture the large majority of well-documented managed-retreat examples involving two or more parties. They originate in 22 countries spanning all major world regions, occur in pre- and post-disaster settings, and address tropical storms, flooding, erosion, earthquakes and tsunamis. The cases are either one-time interventions or programs that have conducted multiple interventions.

This diversity of applications includes several distinct clusters of interventions, such as numerous examples of post-disaster mandatory relocations and locally driven relocation efforts. To understand what drove these discrepancies, we sought to identify criteria that could map the full range of cases while reflecting fundamental differences among clusters. Data on many potential distinguishing factors were assembled to enable systematic cross-case comparison[19]. Our analysis of these various factors revealed that managed-retreat processes were most fundamentally shaped by the relationship and interactions of the two parties involved.

Conceptual model development

We use the two parties' motivations to structure a conceptual model encompassing documented experiences with managed retreat. The model serves as a point of departure for unpacking case-specific complexities. By enabling comparison among vastly different applications, it lays the groundwork for deeper investigation of the various factors shaping the process of managed retreat, such as power dynamics between parties.

In the conceptual model (Fig. 1), the residents' initial willingness to move is reflected in the horizontal axis. Either the residents (those who would be moving) initiate the move, or they do not. On the right-hand side, residents initiate and thus support the move; on the left-hand side, residents do not initiate retreat. The vertical axis encompasses the implementing party's motivation to support managed retreat. The implementing party, often a government entity, represents a broader group of constituents. It is therefore more likely to support retreat when benefits are perceived for that group. The broader group's benefits may include reduced expenditure on disaster relief, improved environmental protection, or reduced exposure to natural hazards. Because the vertical axis is defined in our model from the perspective of the implementing party, it does not necessarily align with the perspective of constituents who might or might not move. For example, an implementing party may define broader benefits on the basis of environmental justice, or in a way that does not account for the importance of a sense of home. The positions of both parties depend on their values and perceived risk levels. Accordingly, different values and misperceptions can affect where each party locates within the model and contribute to misaligned perspectives. Both axes are treated as gradients rather than discrete categories to reflect the nuance and complexity associated with each case.

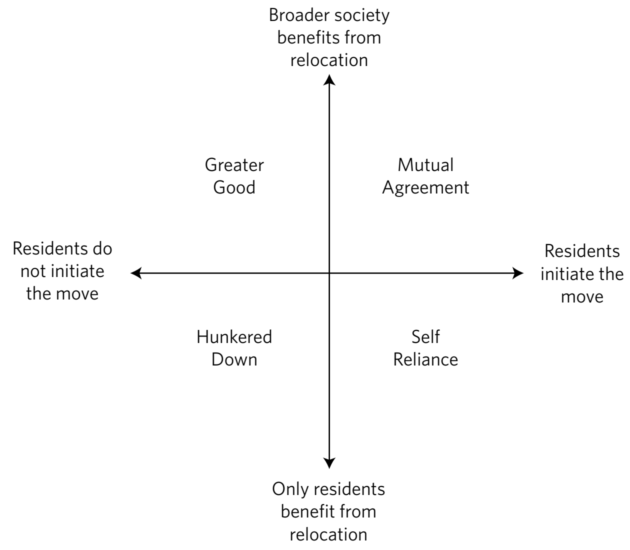

Figure 1 | Conceptual model of managed retreat. The horizontal and vertical axes reflect the perspectives of the residents and implementing party, respectively.

These two axes create four quadrants. In the top-right quadrant, Mutual Agreement, residents initiate retreat and the implementing party likely supports it. In the top-left quadrant, residents do not initiate the move, but broader society would benefit, so the implementing party is motivated to support retreat. Interventions in this Greater Good quadrant often resemble exercises of eminent domain, similar to dam-related resettlements, and may require substantial incentives to persuade residents to relocate. In the bottom-left quadrant, Hunkered Down, residents do not initiate retreat, and broader society benefits little. Managed retreat may occur in such a situation due to other motivating factors, differences between the two parties' valuations of costs and benefits, or misperceptions by either party. Finally, in the bottom-right Self Reliance quadrant, residents support managed retreat, but the implementing party has little incentive to do so.

Understanding recent experiences with managed retreat

Recent experiences demonstrate how each party's motivations shape the processes and outcomes of managed retreat. Each case or cluster of cases is mapped onto the conceptual model in Fig. 2, indicating how the two parties' perspectives vary across the landscape of examples. Supplementary Table 2 provides details for each case.

Post-disaster voluntary relocation programs fall in the Mutual Agreement quadrant because both parties are likely to support implementation of retreat. For example, the US Federal Emergency Management Agency (FEMA) finances property buyouts through the Hazard Mitigation Grant Program (HMGP) (Supplementary Table 2, Example 1). After a disaster, owners of high-risk properties are offered buyouts at the house's pre-disaster market value, and

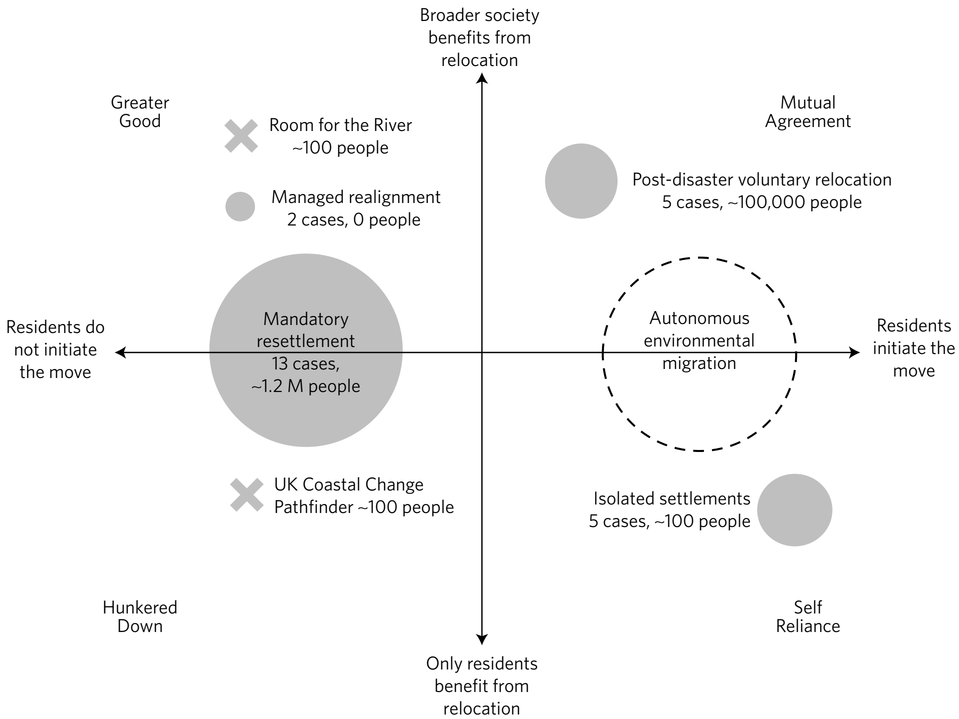

Figure 2 | Managed-retreat conceptual model with recent examples mapped into their respective quadrants. Circles denote sets of cases, and crosses represent single cases. Circle sizes are proportional to the number of cases except for autonomous migration, which falls outside our analysis. The number of people is the approximate number resettled to date. For additional detail on the cases included and the estimated number resettled, see Supplementary Tables 1 and 2.

the property is restored to open space. Benefit–cost ratios for these interventions range between 2 and 5 depending on the types of benefits monetized[20,21]. In some cases (for example, Lockyer Valley, Australia), relocation decisions have been made at the community, rather than household, level (Supplementary Table 2, Example 3)[22]. Most of these interventions have resettled tens to hundreds of households at a time; their voluntary nature can limit their scale.

In Mutual Agreement, aligned interests between parties help overcome regulatory obstacles. For example, in Lockyer Valley, land use change that 'would normally have taken between two and three years to plan and permit was accomplished in four months'[23]. Although widespread agreement advances implementation for this quadrant, resident perspectives can vary within interventions[24]. Some households may initially oppose relocation but concede upon realizing much of their community is moving. Time required to process resettlement can be an obstacle; hesitant residents may find it easier to rebuild and return home than to wait for finalization of the buyout or relocation. Although residents must choose to relocate, the implementing party's support facilitates the retreat process.

Greater Good managed-retreat interventions are driven by a motivated implementing party, which often must overcome initial resident opposition by incentivizing or compelling relocation. As part of the Netherlands' Room for the River program, years of debate between residents, scientists, and government agencies culminated in the decision to lower dykes around the De Noordwaard community, creating a floodplain for high river flows and protecting downstream settlements (Supplementary Table 2, Example 6). The government negotiated with each of 75 affected households, offering to buy out or elevate their homes[17]. In this case, the community's displacement reduced risk for a much larger population.

Similar compensation for affected residents features in managed realignment projects, in which embankments are removed or shifted inland to restore wetlands and reduce spending on coastal defences. The UK and Germany have implemented dozens of these projects over the past several decades (Supplementary Table 2, Examples 7 and 8)[25]. Residents are not displaced but may lose land to realignment. Comprehensive cost and benefit data are lacking, but one such project has been shown to be cost-effective given avoided coastal defence spending and environmental benefits[18].

In Hunkered Down, residents do not initially support retreat, and broader society benefits little from its implementation. For example, in the UK Coastal Change Pathfinder Programme, five local councils relocated or bought out households at high risk from coastal hazards (Supplementary Table 2, Example 22). The residents were offered financial and regulatory relocation support to incentivize their move. However, an ex post analysis concluded that societal costs exceeded benefits for several of the interventions (although it did not consider the benefits of reduced urban blight or other local social and environmental improvements)[26]. The implementing party's decision to implement retreat may have been driven by mistaken perceptions about its costs and benefits or by other non-economic benefits.

Almost half of the cases are categorized as mandatory resettlement projects. The benefits of such interventions are often hotly debated, so their location on the vertical axis is uncertain. Resident reactions are typically negative, varying with resident circumstances, relocation destination, and retreat process[27]. These mandatory resettlements are generally very large in scale, sometimes aiming to move hundreds of thousands of people (see Supplementary Table 1). Because of resident opposition and scale, these interventions have encountered numerous logistical and political challenges. After the tsunami in 2004, the Sri Lankan government prohibited rebuilding in the coastal zone (Supplementary Table 2, Example 19). However, an opaque process, redefinitions of the coastal zone, and lack of trust in the government hampered implementation. Some ultimately moved back to the coastal zone while others lacked permanent housing for many months or years[28].

For Hunkered Down and Greater Good cases, the enabling driver is the implementing party's commitment and capacity to relocate residents despite public resistance, complexities of mobilizing and disbursing funds, and the challenges of determining who moves where. These projects often require coordination across numerous institutions and door-to-door engagement. Nonetheless, in all cases in these two quadrants, much of the target population was relocated due to the implementing party's political will and authority.

The Self Reliance quadrant comprises several examples of residents struggling to persuade an implementing party to support relocation. The Alaskan villages of Newtok, Shishmaref and Kivalina have long sought relocation assistance from the national government (Supplementary Table 2, Example 24). Although previously seasonally migratory, these communities began to settle in the late nineteenth and early twentieth centuries to meet government requirements that their children attend formal schools. The school sites, selected by the US Department of the Interior, led to the tribes' settlement locations. Since then, erosion and flooding have plagued the villages, and each community has decided collectively to relocate. But the villages can only access funds on a competitive basis, in part because these repetitive events do not have the recognition of a presidential disaster declaration. Relocation in such remote locations has a low benefit–cost ratio, and the villages have not been able to fund their relocation thus far[29]. Similarly self-driven, the Pacific island country of Kiribati has sought to enable migration of its residents through bilateral agreements with other nations as well as vocational programs that enhance employment opportunities abroad (Supplementary Table 2, Example 25)[30].

In contrast to the other quadrants, Self Reliance cases have largely failed to resettle the target populations. In addition to financial barriers, residents face legal and institutional obstacles; in the US, for example, no single agency has responsibility to implement the Alaskan villages' relocations[29]. Unlike the Mutual Agreement quadrant, the residents' choosing to relocate is not sufficient for retreat to take place. Instead, residents in Self Reliance cases have fought for tailored solutions for their specific circumstances. For example, after over a decade of discussions with the US government, the Biloxi-Chitimacha-Choctaw tribe in southern Louisiana was able to obtain $50 million for resettlement from the National Disaster Resilience Competition (Supplementary Table 2, Example 27)[31]. These cases demonstrate that small-scale efforts to retreat are not necessarily simpler or easier to achieve than large-scale ones. However, bottom-up efforts with strong community ownership can create customized solutions that top-down interventions may not.

Autonomous environmental migration, also called forced displacement, was not a focus of analysis because it does not strictly meet our definition of managed retreat (see Methods). Because it is resident-initiated, we place it on the right side of our model. However, its vertical-axis location is uncertain. Those moving perceive that the benefits of relocation exceed the costs, but broader societal benefits depend on the origin and destination for each migration context[32,33].

In evaluating these interventions based on available documentation, we can objectively observe the extent to which managed retreat took place. Whether retreat 'should' have taken place and whether it was 'successful' are more difficult to assess. No single quadrant can be defined as 'successful' climate change adaptation, as different groups experience the same intervention in distinct ways. At a minimum, arguably successful adaptation can be found in each quadrant because achieving a specific risk-reduction objective is expected through resettlement.

Lessons from recent experiences

Values, goals and worldviews determine whether or not residents initiate retreat, as well as the implementing party's motivation to support retreat. Residents may oppose retreat despite severe natural hazard risk because of cultural heritage or access to coastal resources; on the other hand, if a destination can preserve valued features, retreat may become more acceptable. The implementing party's values—shaped by its constituent groups—define perceived benefits and costs of retreat. Both parties' viewpoints may evolve over time.

Different sociopolitical dimensions emerge as particularly influential in each quadrant of the conceptual model (Fig. 3). We discuss several salient dimensions here, while underscoring that each case has unique drivers and influences (for example, as illustrated in Fig. 4).

In Mutual Agreement, when the relocation choice is largely left to residents, place attachment and community networks strongly affect the final outcome. At the household or individual level, attachment to place has shaped responses to environmental change and choices regarding risk management[34,35]. Broader social dynamics matter too: after Hurricane Sandy, household- and individual-level characteristics had only a weak influence on the choice to accept or reject a buyout[12]. Rather, the stronger influence was whether or not neighbours were relocating.

For Greater Good interventions, the implementing party's capacity, political will, and power emerge as key influences because it is involved in virtually every step of the process. The implementing party determines who moves, addresses permitting or regulatory issues, and constructs new housing. These interventions are similar to development-driven resettlements, and many of the same risks and lessons that have emerged from those programs apply[36]. For example, the post-tsunami intervention in Sri Lanka demonstrates how insufficient community engagement and weak enforcement can impair retreat efforts (Supplementary Table 2, Example 19). In contrast, after Tropical Storm Stan hit Guatemala, the government-led reconstruction process included consulting the Panabaj and Tz'anchaj communities in selecting a new site and designing houses, ensuring communities' social and cultural priorities were reflected (Supplementary Table 2, Example 14).

The social contract is at the heart of the humanitarian questions surrounding Self Reliance cases. For example, the US government has some obligation to the people of Newtok, Kivalina and Shishmaref (Supplementary Table 2, Example 24), but do those obligations include resettlement when the official analysis suggests it is not in the taxpayers' interest? What if the village locations were largely determined by US government decisions? Such questions will likely become prominent as more communities face increasing risks and confront resettlement.

Future implications for managed retreat

In decades to come, physical and social drivers will shift actuarial and perceived risk levels. For instance, changes in extreme precipitation and sea level rise can increase the likelihood of flooding. For both climatic and non-climatic hazards, risks can also be altered by new policies shaping, for example, flood insurance or lifestyle. For the Alaskan villages, the government-mandated stationary lifestyle reduced mobility and increased vulnerability to coastal hazards[29]. Where perceived risk levels are rising, support for retreat from residents and/or implementing parties is likely to rise as well.

Mutual Agreement situations offer opportunities for both parties to achieve their objectives through managed retreat. To date, Mutual Agreement has been largely limited to post-disaster settings, when perceived risk is high and significant capital is invested in reconstruction. Enabling pre-disaster managed retreat, however, may boost local input and ownership by eliminating the time pressure of post-disaster settings[37]. Identifying Mutual Agreement settings requires the implementing party to monitor changing risk levels, both actuarial and perceived, to delineate where and when

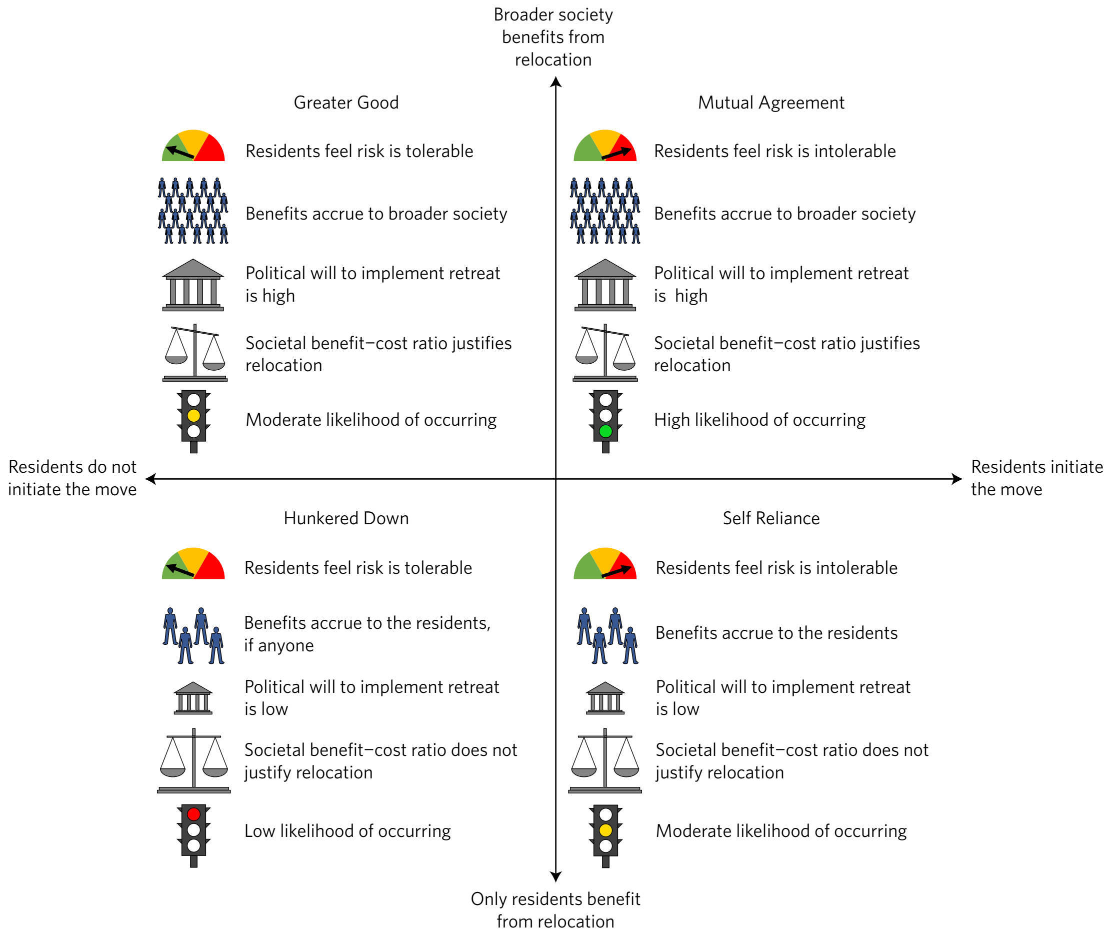

Figure 3 | Key characteristics of each quadrant in the managed-retreat conceptual model. The two axes represent the residents' initial desire to move and the scale of beneficiaries. Political will, societal benefit-cost ratio, and likelihood of occurrence stem from those two factors.

retreat might be encouraged or required. For example, in high-risk areas, a local government may implement regulations that facilitate the eventual removal of structures, for instance by permitting development only for the next twenty years or until the shoreline migrates to a certain point.

If residents are initially unwilling to leave, Greater Good situations may require implementing parties to incentivize retreat. In these cases, developing interventions as a move to opportunity, rather than a move from the familiar, may improve residents' willingness to move. Creating options for communities to stay together and select resettlement locations, as in Sendai after the Great East Japan Earthquake, can preserve social capital and shared identity, increasing the appeal of resettlement (Supplementary Table 2, Example 2)[38]. Those who perceive economic opportunities in resettlement locations, particularly younger residents, have more positive attitudes toward retreat[39,40]. Combining managed retreat with urban regeneration or densification goals embeds resettlement in broader development projects and may improve its social feasibility.

Climate change has been asserted prominently as a driver of Self Reliance cases, and these same cases have been the least effective in relocating targeted populations. Although supporting individuals and households to reduce their reliance on external resources will help avoid these situations, there are likely to be communities that require assistance to move together and preserve their existing networks. Conflicting values and beliefs can create severely misaligned perspectives between parties, inhibiting progress. For example, implementing parties that value economic efficiency may refuse to support managed retreat regardless of the attitude of residents. Further, some of these cases encounter deep, fundamental problems associated with sovereign rights and environmental justice. Empowering these locally led efforts requires reducing political obstacles to retreat—for instance, by making resources available in pre-disaster settings[29].

Resource mobilization is of particular concern for managed retreat given its high upfront costs. On the basis of limited available data, the financial cost of managed retreat (to implementing parties) varies from well over $100,000 per person (Alaskan villages and Isle de Jean Charles) to under $10,000 per person (Fiji and UK Coastal Change Pathfinder). Financial constraints are already forcing governments to re-evaluate the choice to rebuild after disasters, and this dynamic is likely to intensify over time[41]. In the US, however, 'no comprehensive governance framework exists that can evaluate when communities and government agencies need to shift their work from protection in place to community relocation'[29]. Elsewhere, discussions are beginning to take place. In the Federated States of Micronesia, Kosrae has proactively adopted a managed-retreat strategy to redirect development inland[42]. The UK's Shoreline Management Plans have identified locations where the current 'Hold the Line' strategy will no longer be the preferred strategy in the future; retreat—either managed by a government agency or not—is likely to take place[43].

Additional research is required to understand the conditions under which managed retreat should be implemented and how to implement it most effectively across diverse contexts. To improve evaluation of managed retreat, future studies could explore how

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Figure 4 | Images of managed retreat. a, Completed managed realignment scheme at Chowder Ness, UK. The previous coastal defense has been breached, with a new one constructed inland. **b**, An empty lot where a home once stood in Oakwood Beach, New York. Approximately 80% of Oakwood Beach accepted buyouts from the US government after Hurricane Sandy. **c**, A sign demarcating the 'No Build Zone' in the Philippines after Typhoon Haiyan. **d**, Infrastructure damage in Shishmaref, Alaska. Shishmaref is one of several Alaskan villages that has been trying to relocate with little success. Images are reproduced with permission from Associated British Ports (**a**), Nathan Kensinger 2017 (**b**), Veejay Villafranca (**c**) and Ned Rozell (**d**).

economic efficiency criteria can be integrated with attachment to place, heritage, and other social dimensions in decision-making. Such research could also help resolve discrepancies between the perspectives of implementing agencies and residents. Another topic for future research is identifying how attitudes toward managed retreat change with increasing natural hazard risk, which could suggest whether Mutual Agreement managed retreat is likely to become an opportunity in high-risk locales, or whether Greater Good interventions will be necessary. Finally, research exploring novel implementations of managed retreat, such as in pre-disaster voluntary settings, can identify new solutions to thorny social, political and financial barriers. Over years to come, effectively tapping managed retreat will necessitate new approaches for managing trade-offs and facilitating inclusive decision-making. The requisite dialogues and innovations stretch from village scales to international cooperation aiming to keep climate change and its unavoidable damages in check.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

M.H., K.J.M. and C.B.F. conceived the research and developed the conceptual model. M.H. collected and analysed data. M.H. wrote the paper with discussions with and inputs from K.J.M. and C.B.F.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to M.H.

Competing financial interests

The authors declare no competing financial interests.

Methods

Search strategy and selection criteria. We define managed retreat as the strategic relocation of structures or abandonment of land to manage natural hazard risk. However, such actions are often called other terms based on their context; relevant phrases include 'community relocation,' 'climate displacement,' 'island abandonment' and 'planned resettlement.' Each phrase was applied in Web of Science searches. References listed in those papers were used to identify additional cases. To supplement the peer-reviewed literature, a broader internet search was conducted with the same search terms, but only the top ~100 results from those searches were reviewed given the volume of results returned. Searches were conducted in early 2016.

Results were filtered based on fulfilment of the following criteria: the permanent abandonment of land or relocation of people or assets was initiated, not just planned; the action was primarily motivated by natural hazard risk; and it was 'managed'—that is, it was a deliberate intervention involving two or more parties. The first criterion eliminated studies that, for example, surveyed residents for attitudes toward managed retreat or conducted biophysical or economic analyses of a potential managed-retreat intervention—without actual initiation of retreat. The second criterion eliminated other types of resettlement, such as those driven by infrastructure development. The third criterion eliminated autonomous migration or post-disaster forced displacement in which only the individuals or households moving played a role; given the relevance of autonomous environmental migration, we visualize it within our conceptual model but do not examine it in depth. The third criterion also eliminated managed retreat of assets that had virtually no effect on any other party, such as a landowner relocating a parking lot on their own property, in which only the perspective of the implementing party is relevant.

Once cases were identified, a subsequent search specific to each case was conducted to track down the most recent information on the intervention, such as the number of people or households relocated as part of the intervention.

Comparative analysis and conceptual model development. After the 27 cases were identified, several distinct clusters of interventions emerged inductively, such as the numerous examples of post-disaster mandatory relocations and locally driven relocation efforts. We sought to identify criteria that could comprehensively map the identified cases while reflecting fundamental differences among clusters. These factors, such as developed versus developing country, pre-disaster versus post-disaster, and rapid-onset versus slow-onset natural hazard, were identified from case-specific findings of their importance[22,29]. We gathered data on the variables of interest for each case to enable systematic comparison among them[19]. The conceptual model was developed from a comparative analysis of the cases reviewed. Through iterations of model development, it became clear that these managed-retreat processes were, most fundamentally, two-party decisions and negotiations, each taking place in a unique setting. Therefore, we chose to structure the model based on the motivations of the parties interacting in retreat processes.

Data availability. All data used in this study are available in the sources cited in the references sections of the main manuscript and the Supplementary Information. All estimations performed in Supplementary Table 1 are explained in the Notes column, and the analysis underpinning each entry in Supplementary Table 2 is explained in the Supplementary Information.

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Managed retreat as a response to natural hazard risk

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Managed Retreat as a Response to Natural Hazard Risk

Supplementary Table 1. An estimation of the number of people resettled to date through managed retreat. This table provides a central estimate based on well-documented cases and may be over- or under-estimating the true total as a result. When a number of households is reported, the estimate is calculated using the average household size for the relevant country. The confidence in each estimate depends on the type, amount, quality, and consistency of the evidence.[1] The "% Complete" column indicates the percentage of the population targeted for resettlement that has been relocated. 100% signifies completed interventions, and 0% signifies that targeted resettlements of people have not yet occurred. Detailed characterization of each managed-retreat case is provided in Supplementary Table 2.

Case	Estimated Number Relocated	Confidence in Estimate	% Complete	Notes
1. US Hazard Mitigation Grant Program	93,236[2]	Low	100%	36,707 properties were purchased through the HMGP between 1993 and 2011, so 36,707 households was used to estimate the population resettled.[3] This estimate is uncertain in part because statistics covering the full duration of the program were not available.
2. Japan	6,500	Moderate	31%	6,500 people had moved as of March 2016, with a planned total of 21,000.[4]
3. Lockyer Valley, Australia	256[2]	High	100%	100 households owned land in the new site as of August 2011.[5]
4. Pune, India	692[2]	Moderate	100%	152 households resettled.[6]
5. Vunidugoloa, Fiji	128[7]	High	100%	The 26 households from the original Vunidugoloa village were resettled to the new site.[8]
6. De Noordwaard, the Netherlands	83[9]	Low	100%	75 households were resettled, either in elevated mounds or outside of the area, but the division between

				elevated households and relocated households is not available. Half of the estimated potential population is used here.[10]
7. Managed Realignment in the UK	0	High	100%	Coastal defense structures have been breached or moved inland, but no resettlement was reported.[11]
8. Managed Realignment in Germany	0	High	100%	Coastal defense structures have been breached or moved inland, but no resettlement was reported.[11]
9. Argentina	37,522[2]	Moderate	100%	11,911 houses were constructed for the resettlement.[12]
10. Byron Bay, Australia	0	High	100%	No relocation of people or assets occurred.[13]
11. Lower Zambezi, Mozambique	125,000	Moderate	100%	Reported figures vary from 110,000 – 140,000 people.[14,15]
12. Sao Paulo, Brazil	24,311[2]	Moderate	100%	7,544 households were resettled.[12]
13. Nueva Esperanza, Colombia	3,952[2]	Moderate	100%	1,074 households were resettled.[12]
14. Panabaj and Tz'anchaj, Guatemala	4,758[16]	Moderate	100%	915 households were resettled.[12]
15. Aceh, Indonesia	186,000[17]	Low	100%	The post-tsunami coastal setback zone was not strictly enforced, so it cannot be determined which rebuilt homes had been relocated and which were built in the same place. It is possible at the extreme that no relocation from the coastal zone occurred.[18] Half of the estimated potential population is used here.
16. Mekong Delta, Vietnam	500,000	Low	100%	A reported 1 million people either moved and or had their houses elevated.[19] Half of that figure is used as the estimate here.

17. Christchurch, New Zealand	20,592[2]	Moderate	95%	7,800 households (representing 95% of total) had reached agreement with the government to sell their houses.[20]
18. Philippines	82,926[2]	Moderate	9%	19,330 houses have been constructed for those displaced by the no-build zone as of March 2016. 205,000 total houses are planned.[21]
19. Sri Lanka	126,000[22]	Moderate	91%	As of January 2006, approximately 30,000 MOUs had been signed for 32,000 - 33,000 households displaced by the buffer zone.[23]
20. Ab-bar, Iran	988	High	100%	Estimate assumes that all 988 people from Balklor and Jamal Abad resettled into Ab-bar.[24]
21. Tamil Nadu, India	100,183[2]	High	100%	Funds were allocated for the construction of 22,000 homes for those who were living within 0 and 200m from the coastline in Tamil Nadu.[25]
22. UK Coastal Change Pathfinder	110[2]	Moderate	100%	47 households were bought out or relocated across multiple locations.[26]
23. Gunayala, Panama	0	High	0%	As of April 2015, no resettlement had occurred.[27]
24. Alaskan villages, US	0	High	0%	As of August 2015, no resettlement had occurred, but construction has begun at the relocation site.[28]
25. Kiribati	0	Low	0%	Migration from Kiribati occurs through education and employment programs, and it is unclear how many relocations are driven by natural hazard risk.[29]

26. Carteret Islands, Papua New Guinea	101	Moderate	6%	Figures are as of July 2015.[30]
27. Isle de Jean Charles, Louisiana, US	0	High	0%	Multiple sources report that no resettlement has taken place yet. The total number to be resettled is uncertain; New York Times reports that only 60 people remain on the island, but Louisiana's funding application indicates a total of 100 families to be moved.[31,32]
Total	**1.3M**			

Supplementary Table 2. Characterizations of each managed-retreat case analyzed in developing a conceptual model for retreat. Further information on the definitions of specific columns is available below the table. Table entries are based on available documentation. MA: Mutual Agreement quadrant of managed-retreat model (Figure 1); GG: Greater Good; HD: Hunkered Down; SR: Self Reliance.

Case Location (Category): Description								
Approx. Dates	Initiator	Implementing / enabling party	Benefit-cost ratio	Whose exposure was reduced?	Natural hazard (Role of climate change asserted)	Implementer involvement	Targeted population	Retreat implemented?
1. US Hazard Mitigation Grant Program (MA): Since at least 1989, the Federal Emergency Management Agency (FEMA) has used its Hazard Mitigation Grant Program to purchase properties from willing homeowners after disasters. The land is restored to open space.[33–35]								
1989-	Residents	Local and national government	+	Residents	Flood, tropical storm, others (Varies)	Moderate	Small - Medium	Yes
2. Japan (MA): After the Great East Japan Earthquake in March 2011, the Japanese government provided funds for communities to rebuild in new locations if they chose. Resettlement locations were determined by the communities. [36]								
2011-	Residents	National government	?	Residents	Earthquake, tsunami (N/A)	Moderate	Large	Partly
3. Lockyer Valley, Australia (MA): A flash flood in 2011 led the Lockyer Valley Regional Council to decide to resettle the entire community on a hillside 50m away. The state and national governments were hesitant at first, but ultimately supported the move.[5,37]								
2011-2014	Residents and local government	State and national government	?	Residents	Riverine flood (Low)	Moderate	Small	Yes
4. Pune, India (MA): Local NGO Shelter Associates led efforts to resettle 152 families from a flood-prone urban slum to newly constructed housing. The funding was raised through a combination of household savings, loans, and government subsidies.[6]								
1997-2004	Residents, NGO	State and national government	?	Residents	Riverine flood (Low)	High	Small	Yes
5. Vunidugoloa, Fiji (MA): Due to flooding and erosion, a coastal village of 26 households on Vanua Levu, Fiji, approached the government for financial assistance to relocate in 2007. The move was completed in 2014 with government support. The villagers contributed to site selection and design.[8]								

Approx. Dates	Initiator	Implementing / enabling party	Benefit-cost ratio	Whose exposure was reduced?	Natural hazard (Role of climate change asserted)	Implementer involvement	Targeted population	Retreat implemented?
Case Location (Category): Description								
2007-2014	Residents	National government	?	Residents	Coastal hazards (High)	Moderate	Small	Yes
6. De Noordwaard, NL (GG): As part of the Room for the River program, a lengthy community engagement process was conducted to decide how to improve the existing flood risk management system to cope with future climate extremes. This resulted in the decision to lower the dikes surrounding De Noordwaard, and the government supported the resettlement of 75 displaced households.[10,38]								
2009-2014	Local government	Local and national government	+	Broader society	Riverine flood (High)	High	Small	Yes
7. Managed Realignment in the UK (GG): Managed realignment has been implemented on dozens of sites in the UK to provide intertidal habitat and reduce flood risk. Some interventions create new habitat to compensate for area lost to development or coastal squeeze.[11,39,40]								
1991-	National government	National government	+	No one	Coastal hazards (Varies)	High	Small	Yes
8. Managed Realignment in Germany (GG): Managed realignment has been implemented on dozens of sites in Germany to provide intertidal habitat and reduce flood risk. Some interventions create new habitat to compensate for area lost to development or coastal squeeze.[11]								
1989-	National government	National government	?	No one	Coastal hazards (Varies)	High	Small	Yes
9. Argentina (GG/HD): Housing programs financed by the national government and multilateral development banks constructed over 10,000 houses over 13 years to resettle low-income groups out of flood-prone areas. The abandoned areas were restored to green space.[12]								
1993-2006	National government	National government, development agencies	?	Residents	Riverine flood (Low)	High	Large	Yes
10. Byron Bay, Australia (GG/HD): Byron Shire Council adopted a policy of retreat in 1988, such that structures would have to be removed once the eroding coastline was at a certain proximity. However, landowners sued the Council on the grounds that the policy devalues their property, which led to revision of the retreat policy.[13]								
1988-2011	Local government	Local government	?	No one	Coastal hazards (High)	High	Small	No

Case Location (Category): Description								
Approx. Dates	Initiator	Implementing / enabling party	Benefit-cost ratio	Whose exposure was reduced?	Natural hazard (Role of climate change asserted)	Implementer involvement	Targeted population	Retreat implemented?
11. Lower Zambezi, Mozambique (GG/HD): Following floods on the Lower Zambezi in 2007, the government resettled 56,000 households out of flood-prone areas. Relocation was not technically mandatory, but the government withdrew basic services in the flood-prone areas and provided social infrastructure in the new locations. The end date of the resettlement program is uncertain.[14,15,41]								
2007-?	National government	National government	?	Residents	Riverine flood (High)	High	Large	Yes
12. Sao Paulo, Brazil (GG/HD): The Brazilian government relocated 7,500 families out of *favelas* in low-lying areas of Sao Paulo, giving them the option to select between several alternative housing locations to minimize community disruption. The program also improved drainage infrastructure.[12]								
1987-2007	National government	National government, development agencies	?	Residents and broader society	Riverine flood (Low)	High	Large	Yes
13. Nueva Esperanza, Colombia (GG/HD): The Nueva Esperanza neighborhood was at risk from landslides and flooding. The property of approximately 1,000 families was purchased, and the government assisted in their resettlement.[12]								
2004-2010	National government	National government	?	Residents	Landslide, flood (Low)	High	Medium	Yes .
14. Panabaj and Tz'anchaj, Guatemala (GG/HD): Tropical Storm Stan in 2005 displaced 900 households from the Panabaj and Tz'anchaj districts of Guatemala. The relocation process was led by the government, and communities were involved in selecting and designing the resettlement site.[12]								
2005-2010	National government	National government	?	Residents	Tropical storm (Low)	High	Medium	Yes
15. Aceh, Indonesia (GG/HD): Following the Indian Ocean tsunami of 2004, the Aceh province implemented coastal regulations to reduce settlements in close proximity to the coast. Because the ban was not strictly enforced, it is unclear to what extent people were resettled outside of the coastal zone. For the same reason, the end date of this intervention is unclear.[42–44]								
2004-?	National government	National government	?	Residents	Tsunami (N/A)	High	Large	Partly
16. Mekong Delta, Vietnam (GG/HD): Launched in 1996, the Vietnam government's Living with the Flood policy resettled 1 million people (as of 2005) who were living in flood-prone areas of the Mekong Delta. Resettlement clusters were constructed outside of the flood zone or at an elevation above the record flood level.[19]								
1996-2005	National government	National government	?	Residents	Riverine flood (Low)	High	Large	Yes

Case Location (Category): Description								
Approx. Dates	Initiator	Implementing / enabling party	Benefit-cost ratio	Whose exposure was reduced?	Natural hazard (Role of climate change asserted)	Implementer involvement	Targeted population	Retreat implemented?
17. Christchurch, NZ (GG/HD): A series of large earthquakes from 2010-2011 led the New Zealand government to declare a "residential red zone." 7,800 property owners had agreed to sell their property to the government as of April 2015, but the relocation process was still ongoing.[20,45]								
2011-	National government	National government	?	Residents	Earthquake (N/A)	Moderate	Large	Yes
18. Philippines (GG/HD): The "no build zone" declared after Typhoon Haiyan struck in September 2013 prohibited residential dwellings within 40m of the high water mark. It was estimated that over 200,000 new houses would be built.[21,46]								
2013-	National government	National government	?	Residents	Tropical storm (Low)	High	Large	Partly
19. Sri Lanka (GG/HD): A coastal buffer zone was declared in Sri Lanka after the 2004 Indian Ocean tsunami. It was scaled back from 500m initially down to 100m. Approximately 30,000 households were displaced as a result of the buffer zone. The end date of the resettlement program is uncertain.[23,42,47]								
2004-?	National government	National government	?	Residents	Tsunami (N/A)	High	Large	Yes
20. Ab-bar, Iran (GG/HD): After the Manjil earthquake in 1990, approximately 210 families from two other villages were resettled in the village of Ab-bar.[24]								
1990-1991	National government	National government	?	Residents	Earthquake (N/A)	High	Small	Yes
21. Tamil Nadu, India (GG/HD): After the 2004 Indian Ocean tsunami, the government of Tamil Nadu allocated funds to resettle 22,000 households that had been living between 0 and 200m from the coast. Relocation was optional for houses between 200 and 500m from the coast. The end date of the resettlement program is uncertain.[25]								
2004-?	State government	State government	?	Residents	Tsunami (N/A)	High	Large	Yes
22. UK Coastal Change Pathfinder (HD): The UK government's Coastal Change Pathfinder Programme funded five pilots to test "rollback" schemes, buying out property at high risk from erosion. Each pilot relocated about ten households.[26]								
2009-2011	Local government	National and local government	-	Residents	Coastal hazards (High)	High	Small	Yes
23. Gunayala, Panama (SR): 300 families on Gardi Sugdub island voted to relocate in 2010 and acquired land on the mainland of Panama. The Ministry of Housing has outlined a plan for the new settlement, but no new houses have been constructed.[27,48]								

Approx. Dates	Initiator	Implementing / enabling party	Benefit-cost ratio	Whose exposure was reduced?	Natural hazard (Role of climate change asserted)	Implementer involvement	Targeted population	Retreat implemented?
Case Location (Category): Description								
2010-	Residents	National government	?	Residents	Coastal hazards (High)	Moderate	Medium	No (little progress)
24. Alaskan villages, US (SR): The Alaskan villages of Newtok, Shishmaref, and Kivalina have all voted to relocate as their villages are affected by erosion and flooding. Despite decades of effort, none of the villages has been able to completely relocate.[49,50]								
1996-	Residents	National and state government	-	Residents	Coastal hazards (High)	Low	Small	No (little progress)
25. Kiribati (SR): Driven by former president Anote Tong, Kiribati has sought to enhance opportunities for its citizens to move abroad. In May 2014, the government purchased land in Fiji as a potential resettlement site.[51,52]								
2010-	Residents, national government	International community	?	Residents	Coastal hazards (High)	Low	Unknown	No (little progress)
26. Carteret Islands, Papua New Guinea (SR): In 2006, Carteret Islanders created a non-profit Tulele Peisa to organize the relocation of 1,700 people.[53] As of 2015, the goal was to relocate 150 families, of which eight families had already relocated.[30]								
2005-	Residents	National government	?	Residents	Coastal hazards (High)	Low	Medium	No (little progress)
27. Isle de Jean Charles, Louisiana, US (SR): The Isle de Jean Charles band of Biloxi-Chitimacha-Choctaw Indians in southern Louisiana has been discussing resettlement with the US Army Corps of Engineers since 2002. In early 2016, they were awarded funding to relocate farther north.[50]								
2002-	Residents	National government	?	Residents	Coastal hazards (High)	Moderate	Small	No (little progress)

Supplementary Table 2

- *Approximate dates:* the year marking the start of the intervention or program, and the year in which it concluded. Some cases are ongoing and thus have no end date. For others, denoted with "?", evidence suggests that the intervention is likely complete or close to complete, but the end date is not specified. Dates are often uncertain based on available documentation, for instance because interventions may begin very informally or because the date of official completion of resettlement may not be recorded.
- *Initiator:* the party predominantly responsible for the decision to initiate managed retreat.
- *Implementing/enabling party:* the party predominantly responsible for enabling or compelling managed retreat to take place.
- *Benefit-cost ratio:* the ratio of benefits to costs deriving from the intervention. The methodologies of the cost-benefit analyses differ. + : benefit-cost ratio > 1; – : benefit-cost ratio < 1; ? : benefit-cost ratio for the intervention could not be found in available documentation.
- *Whose exposure was reduced?:* This column describes which parties experienced a reduction in their likelihood of experiencing the natural hazard as a result of the intervention. Most frequently, the residents who are relocated experience this reduction in exposure. Reduction in exposure for broader society was only included when it was an explicit goal of the intervention (e.g., in De Noordwaard). For the managed realignment cases in the UK and Germany, it is possible that the level of protection afforded by the realigned coastline is either equivalent to or less than the previous level of protection, so there is no conclusive reduction in exposure.
- *Natural hazard:* the primary hazard or hazards that drove the decision to initiate retreat.
- *Role of climate change asserted:* the extent to which climate change was asserted to affect the natural hazard and/or the decision to implement retreat, based on the literature available. N/A: the natural hazard was not climate-related; Low: climate change was barely or not at all mentioned in the literature describing the intervention; High: climate change consistently featured in the literature; Varies: the case is a program that has carried out multiple interventions, and the asserted role of climate change is high for some interventions and low for others.
- *Implementer involvement:* This column describes the division of responsibilities between the implementing party and the residents with respect to five components of retreat: decision to retreat, identification of resettlement locations, mobilization of funds, acquisition of permits and approvals, and provision of new housing. Responsibility for each component was ascribed to the implementing party, residents, or both, with responsibility shared between them. In some cases, a component was "not applicable" because it was not part of the intervention (e.g., if no new permits were required). High: implementing party or shared responsibility for 75% or more of the applicable components; Moderate: implementing party or shared responsibility for 25-74% of the applicable components; Low: implementing party or shared responsibility for less than 25% of the applicable components.
- *Targeted scale:* the number of people who were targeted for relocation. For sets of interventions, such as the US Hazard Mitigation Grant Program, this refers to the scale of single interventions. Large: >10,000 people; medium: 1,000-10,000 people; small: <1,000 people. See Supplementary Table 1 for specific estimates associated with each case.

- *Retreat implemented?:* the extent to which those targeted for relocation have been resettled. This column refers to the current state of affairs. Yes: the vast majority of those targeted for managed retreat have been resettled; Partly: some of those targeted for managed retreat have been resettled, either because the intervention was not entirely successful or because it is still underway; No (little progress): very few, if any, of those targeted for managed retreat have been resettled

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