SYNTHESIS OF INDICATORS, DATASETS, AND FRAMEWORKS AVAILABLE TO ESTABLISH RESILIENCE AND ADAPTATION INDICATORS: CASE STUDY OF CHESAPEAKE BAY REGION, USA

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Abstract

Purpose of the Review

One way to comprehensively assess adaptation is through indicators -- a promising decision support tool because they can be designed to efficiently and comprehensively summarize system behavior even if significant uncertainty exists. In this paper, we review the available information applicable to resilience indicators for the Chesapeake Bay region of the U.S.

Recent Findings

We develop a general resilience framework through literature and stakeholder engagement. Using systematic search methods we identified and qualitatively assessed 283 relevant documents. Predominant themes emerge around key regional impacts -- sea level rise, water quality, flooding, and aquatic ecosystems -- as well as magnitude of, exposure to, and impacts of climate hazards.

Summary

Though information was more available for hazards and exposures, relatively little information was found for designing indicators for capacity as well as coping and adaptive responses. Thus, much work remains in translating the existing information landscape into actionable indicators.

Keywords: climate change, adaptation, resilience, framework, indicators, decision support

Declarations

Funding

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Conflicts of interest/Competing interests

none

Availability of data and material

Coded themes and resulting document clusters are available upon request

Code availability (software application or custom code)

Not applicable

Authors' contributions

Kenney: conceptualization, methodology, investigation, data development, manuscript writing original and revision, supervision, project administration, funding acquisition

Gerst: conceptualization, methodology, validation, formal analysis, data curation, manuscript writing original and revision, visualization, funding acquisition

Introduction

One of the greatest challenges for climate adaptation is providing actionable information to make decisions and assess the effectiveness of such actions [1,2]. This is because adaptation decisions are coupled with socio-ecological systems; these are complex systems where the causality between decisions and system behavior occurs across multiple scales and is difficult to predict. An approach to managing this complexity is to use indicators of key phenomena or management objectives [3,4]. Indicators help do this by systematically choosing metrics that are likely to summarize key complex behaviors. In addition, they are regularly updated and compared to a status quo baseline, which is essential for supporting decision-making and assessing change over time [5]. There has been increased interest and a need for continued research by both the academic and practitioner communities in the development and use of adaptation indicators to track both adaptation activities (progress indicators) and adaptation success (effectiveness indicators) [4,6–9].

Developing and tracking indicators for a specific adaptation, as opposed to multiple adaptation actions, is more straightforward. With one adaptation decision, goals are easier to define, which makes linking indicators to goals less arduous. In particular, using a decision analytic approach, the climate impact information can be customized for that location, the indicators can directly link to the goals of the project and be used to select the project, and the same set of indicators, using an adaptive management approach, can evaluate whether a decision needs to be revisited to meet the project goals [10–12].

In contrast, developing indicators to assess multiple adaptation actions within a community or region is more challenging, because there are not consistent goals across projects, there may be different decision-makers and values for each project, and thus, there are not a universal set of indicators that will assess whether projects are successful [13]. Additionally, because an undesirable change for a particular indicator does not necessarily mean the project is not successful (i.e., a project designed to slow property impacts due to sea level rise damage), developing a counterfactual is critical to assess whether adaptation actions have made things less bad than it would be otherwise. In particular, the goal of such adaptation actions is to minimize risk [7]. As a result, the majority of multi-project adaptation indicators focus on process indicators, which measure whether there is activity and progress that is intended to produce positive outcomes. These indicators are easy to identify and measure, which is why they are more widely used; however, such indicators do not measure whether or not adaptation projects are successful. For example, a process indicator would be the number of adaptation projects in a region, as opposed to an effectiveness indicator measuring the effect of each project [14].

Overall, adaptation indicators are also difficult because the actions that can be pursued are more than just physical or nature-based infrastructure projects. Specifically, from the typology of adaptation actions, as defined by Biagini et al. [15] include: “administrative/institutional/organizational, behavioral, educational, financial, legal/legislative, market mechanisms, managerial, political, practical, regulatory, research and/or development, structural/infrastructural, and technological.” Developing effectiveness indicators for some of these types of indicators, such as behavioral, are challenging because a particular intervention may be one of many activities that have influenced changes, and thus assessing the effectiveness when there are multiple factors is difficult to attribute causally.

To tackle the challenges, one approach is to recognize that adaptation effectiveness is a latent concept that could be represented and measured in some way through greater regional resilience. The concept of resilience is one that lacks a single definition and instead is defined by several properties that are inherent in a system which can be further defined through indicators [16]. In particular, in order to measure the effectiveness of multiple adaptation actions, an effective strategy is to broaden the system boundary and treat adaptation as a process (i.e., an action within a system), with system resilience being a structural system property, much like flexibility or reliability. Adaptation actions that on the whole reduce risk [7], increase system resilience as compared to a status quo counterfactual. Broadening the system boundary to consider system resilience increases the complexity and measurement problems. In doing so, it is important not to develop indicators that aggregate such latent concepts such as vulnerability and resilience into a unitless metric [17,18]; such aggregation hides the inherent complexity of the system and requires weighting of the different components, which makes the assessment of the limiting resilience factors harder to identify. Thus, such an approach requires developing a shared definition and understanding of resilience, the information landscape, and gaps to measure such indicators; hence, a detailed literature review and analysis are necessary to understand our current ability to develop adaptation and resilience indicators.

The objective of this paper is to conduct a document analysis by reviewing literature, datasets, frameworks, and indicators to support the development of adaptation indicators. To analyze the current landscape of information, we developed a resilience framework through both a literature synthesis and engagement with regional experts who have led efforts to fund or implement adaptation projects. To provide specificity, the review and analysis were focused on the Chesapeake Bay region of the U.S., a region that is both experiencing intense coastal climate impacts and has taken responsive adaptive actions. We focus both on identifying information-rich areas as well as gaps that will need to be addressed in order to understand resilience and adaptation effectiveness more holistically.

Methods

To understand the landscape of climate adaptation indicators, datasets, and frameworks, we adopted a resilience framework to understand what aspects of resilience are well developed and what aspects need to be further established in order to have robust adaptation effectiveness indicators. The method includes i) establishment of a general resilience framework and associated definitions, iii) case study location, and iii) document identification and application of resilience framework to document analysis.

General Resilience Framework

This primarily involves collaborative work with project partners and secondarily the use of focus groups composed of state and local-level stakeholders, which will be facilitated by the project investigators. The collaborative work and focus groups will be guided through a two-part process: 1) conceptual modeling and 2) indicator scoping.

Drawing on past efforts to establish indicators of climate change, impacts, and responses [5], we used a conceptual modeling process to establish a guide that stakeholders can use to define the concept of resilience, the system bounds, and to select indicators [16]. Conceptual modeling is used for many applications beyond indicator development, including formal model building and group decision-making [19]. In this context, the purpose of a conceptual model is to allow stakeholders to be explicit about what drivers and causal processes they believe are important in assessing resilience. It is based on the idea that indicators provide summaries of the behavior of complex systems, which usually contain an unmanageably large number of variables that could be tracked by end-users. The conceptual modeling process is in contrast to other indicator development processes, which do not necessarily root indicator selection in the stakeholder's understanding of system behavior. As a result, a set of indicators could be selected that do not provide adequate coverage across the system of interest.

By eliciting these views in a controlled environment, the conceptual modeling process provides checks on the consistency and plausibility of the resulting indicator system [20]. As the models are visual aids, participants can use them as common points of discussion (termed boundary objects the scientific literature [21]), yielding the incorporation of multiple perspectives.

Conceptual models can also capture scale, which is important to flexible indicator systems. Scale can be represented by noting that local concerns are often nested in broader systems. For example, local hydrology is dependent on its regional watershed, and local government is constrained and enabled by policies enacted at the state level. Stakeholders can decide where to draw the boundary and scope of their indicator system, as well as articulate greater detail within any of the aggregate systems shown, such as infrastructure.

To give additional structure to the conceptual modeling process and seed the step of indicator scoping, we prompted a group of stakeholders to consider the determinants of resilience (Figure 2) that we have synthesized from the scientific review literature [22]. This approach is similar to framework synthesis methods, where an initial conceptual model is grounded in background knowledge and initial literature searches and subsequently modified by more in-depth systematic searches [23] . The underlying concept is that for resilience to be completely tracked, a baseline must be established along the causal chain from hazard to decisions (shown in blue) to impact. This is a distinctly different style of resilience or adaptation indicator than aggregate indices that provide a single score [24], as it allows users to assess cause-and-effect and trade-offs among potential decisions.

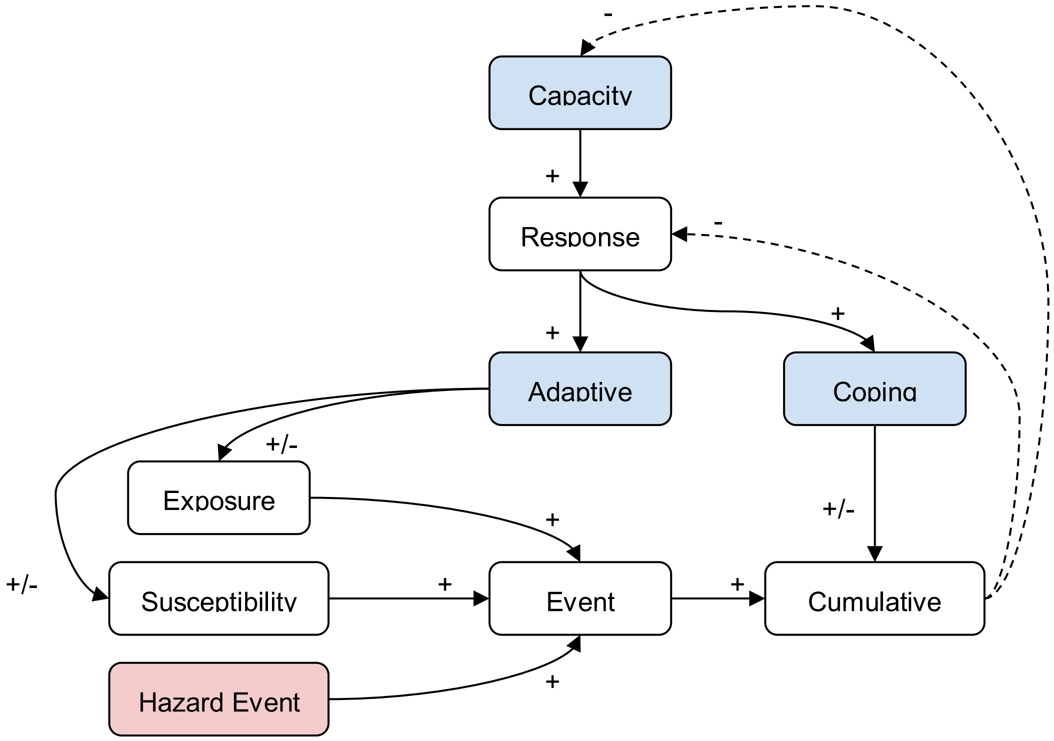

Figure 1. Conceptual model of determinants of resilience. Arrows represent cause-and-effect. Plus, (+) markers indicate an increase (decrease) in one determinant leads to an increase (decrease) in another. Negative (-) markers indicate an increase (decrease) in one determinant leads to an decrease (increase) in another. Some connections can be plus or minus. Dashed lines represent feedbacks that happen over time. Blue boxes are actions that can be taken to improve resilience.

The final conceptual model used in the analysis is shown in Figure 1. It emphasizes that resilience is an emergent system property that is dependent on the balance between reduction of cumulative impacts, as determined by individual event impacts and coping responses, and the potentially erosive feedback of cumulative impacts on capacity (dashed lines). The causal logic starts with individual *hazard events*, which refer to physical events that may produce damaging impacts on people, assets, or ecosystems. Hazard measurements include frequency of occurrence, average, and extreme value statistics as well as characteristics of specific hazard events.

Impact events and cumulative impacts to people, assets, or ecosystems do not occur unless they are exposed and susceptible to hazards. *Exposure* measures the amount of a community's people, assets, or ecosystems that are subject to hazard. Exposure indicators are calculated from data on value, location, and physical dimensions, such as number of people, miles of shoreline, and property value. *Susceptibility* describes qualities of people, assets, or ecosystems that lead them to be vulnerable to a hazard event, such as the percentage of a population that is elderly or type building material and design.

Capacity refers to the ability of a community to plan and act. Capacity building includes processes that increase a community's ability to obtain knowledge, skills, and equipment to support responses; response capacity includes actions intended to increase resilience that occur as a result of capacity building. Response capacity influences the ability to overcome adverse conditions in the short to medium term (coping response) and to make changes to reduce future impacts (adaptive response).

One key aspect of our conceptual model is that impacts are cumulative over time, but may be reduced by coping responses, such as administering medical care or rebuilding a bridge. However, the correct coping response is not always known, so the model allows for responses to worsen cumulative impact. Similarly, adaptive responses can lessen exposure and susceptibility so that the next hazard event creates less of an impact. Adaptive responses also have the potential to increase the risk of climate-related impacts, an outcome commonly known as maladaptation.

Finally, capacity building and response decisions increase adaptive and coping responses. It is here through which feedback from cumulative impact can be felt, as lingering cumulative impact can erode the ability to build capacity as well as the response capacity itself. Thus, resilience is ultimately about having the capacity to avoid a destructive feedback loop that can lock a community into a less desirable state.

Case Study Location: Chesapeake Bay

To provide depth and specificity to the analysis, we chose to apply the framework to the Chesapeake Bay Region, USA. The Chesapeake Bay Region is the largest estuary in the U.S. [25]. The full drainage basin covers 165,800 km^2 with ten major rivers, including the Potomac, Patuxent, Rappahannock, Susquehanna and James rivers, in parts of six states (Delaware, Maryland, New York, Pennsylvania, Virginia and West Virginia) plus all of Washington, D.C.. The Bay itself has a surface area of approximately 11,400 km^2 and extends 332 km in length [25]. The Chesapeake Bay includes portions that are freshwater, brackish and saline, and encompasses many diverse habitats including forests, marshes, submerged aquatic vegetation and oyster reefs. As such it is home to a wide diversity of species including over 300 species of fish, shellfish and crab (such as Atlantic menhaden, striped bass, American eel [26], eastern oyster, and blue crab [27]). The Bay is also home to over 18 million people [25] with a highly productive economy based particularly on fishing, recreation, tourism, and real estate, that is estimated at over a trillion dollars per year [28].

This region is facing significant local climatic change impacts, most notably sea level rise, high heat (including implications for water temperature), heavy precipitation, and intensity of hurricanes [29]. As a result, there is a high degree of both activities and interest by local and state government in the region [30,31] and opportunities for regional scale assessment of adaptation effectiveness which has not been deployed systematically beyond a project scale assessment. Thus, there is interest in developing resilience indicators to support climate adaptation assessment [32].

Document Identification and Analysis

We built on a dataset that was developed for a qualitative review by Teodoro and Nairn [33]. The relevant documents (n=283) were comprised of both peer-reviewed journal and report literature published between 2007-2018 and were selected from a population of n=2988 documents given criteria which removed redundancies, removed web-only content, and finally screened for relevance.

The data were analyzed using QSR International's NVivo qualitative data analysis software version 12.3 [34]. We built upon the initial dataset developed by Teodoro and Nairn [35] which drew from methods developed by Saldaña [36] to code the documents given climate hazard and adaptation themes, geographic focus, type of document, and type of author. Specifically, we coded the documents additionally for the resilience categories represented and discussed in the general resilience framework above.

We analyzed the document/effect clustering (see Technical Appendix), to assess which documents are similar enough to each other to be summarized together and to identify clusters that are dissimilar enough to highlight important differences. To identify the appropriate number of clusters, we used a cluster validity index, Calinski-Harabasz (CH) index, which performed well across a range of data structures [37–39]. This analysis allowed us to analyze the climate effects, resilience categories, and information types across all the documents to identify patterns which help us to understand the current information landscape for establishing resilience and adaptation indicators.

Results

At 49% of documents, sea level rise is by far the most frequent climate theme (Figure 2). In general, coastal themes, including water quality, flooding, and ecosystems, are emphasized over terrestrial ecosystems, phenology, and health. This is not surprising given the prominence of the Chesapeake Bay in Maryland climate change discourses.

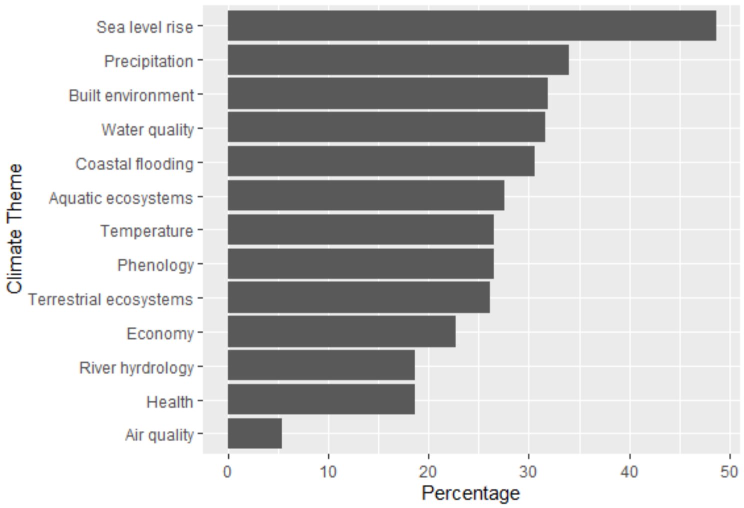

Figure 2. Percentage of documents that address each theme; n = 294.

In total, there are 186 unique combinations of climate themes addressed by the collected documents; presenting an analysis of each combination is prohibitive. As an alternative, we group documents together based on the similarity of their theme combinations, and analyze their aggregate attributes. Using an agglomerative hierarchical clustering algorithm (see Technical Appendix methods), we find that documents can be categorized into 14 groups, which have widely varying theme combinations (Figure 3).

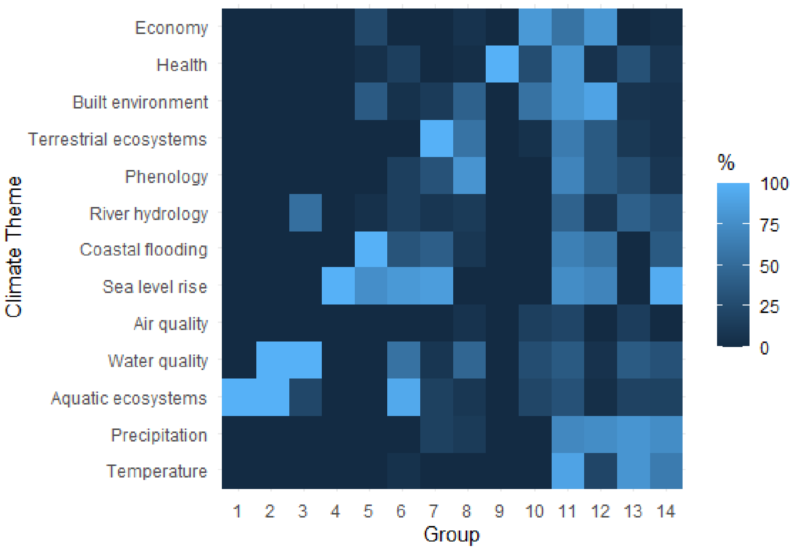

Figure 3. Heatmap of groups and climate themes. Cell color scale of row i and column j corresponds to the percent of documents in each group j that address effect i.

As the groups in Figure 3 were produced using hierarchical clustering, groups near one another are more similar and can be summarized into higher level groups. Groups 1-3 are targeted towards water quality and ecosystems, with slight variations in the focus among groups, and overall make up the smallest fraction of the documents collected (Figure 4). Group 2 contains scientific contributions [40–44] to understanding the sensitivity of water quality and aquatic ecosystems, as well as indicator-based report cards [45–47], while group 3 addresses nutrient impacts and management in terms of the science [48–52] and reporting of progress [53]. In contrast, group 1 predominantly consists of reports and fact sheets showing impact indicators for Chesapeake Bay ecosystems.

Groups 4-7 are related to one another by their relatively greater focus on sea level rise. Group 4 addresses only sea level rise, while groups 5-7 all address sea level rise and its interaction with another theme. Specifically, group 4 mostly contains state-level reports on the hazard and exposure of sea level rise to Maryland [54–57]. Group 5 addresses sea level rise and coastal flooding from a social science of adaptation [54] and planning perspectives [58–62] and group 6 focuses more on sea level rise and its effect on ecosystems [63], while Group 7 is thematically less well-defined. Groups 8-10 tend to focus on a mix of specific impact types unrelated to sea level rise, such as soils and erosion [64–66], hydrology [67–69], terrestrial biodiversity [70–72], and state-level health impacts in Maryland [73–75].

Groups 11 and 12 mostly consist of planning documents, mostly hazard mitigation plans [76–81] and adaptation plans [82–85], and economic impact analyses [69,86,87]. In general, these two groups are the most comprehensive in terms of climate themes. In contrast, Groups 13 and 14 are much more focused on the effects of temperature and precipitation extreme events [88–91].

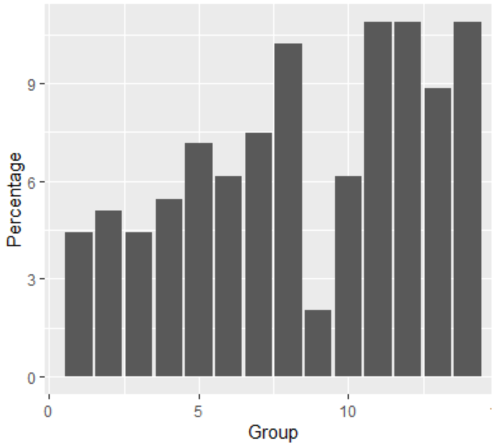

Figure 4. Documents (in %) per group.

Comparison across groups shows that the combination of themes are diverse and that information on resilience can be found across a wide array of documents. The differences in document content with respect to effects is somewhat mirrored in the type of resilience categories addressed. For example, groups 1-3, which are heavily focused on aquatic ecosystems and water quality, address impacts to natural systems at a relatively high rate while having little to nor coverage of capacity and response (Figure 5).

Within groups 4-7, groups 4 and 6 are concentrated on a single resilience category, while groups 5 and 7 contain more diverse resilience categories. This is because group 4 focuses solely on sea level rise, and hence, the resilience category hazard, while group 6 covers sea level rise and effects on aquatic ecosystems, which is more impact-related. In contrast, group 5 contains documents with a broader focus on sea level rise and adaptation to coastal flooding, which is associated with a more comprehensive set of resilience categories. Similarly, groups 11 and 12 are mostly composed hazard and adaptation documents, which by design incorporate more resilience categories. Relative to other groups, they also have a larger concentration of documents with content related to response capacity and tracking responses.

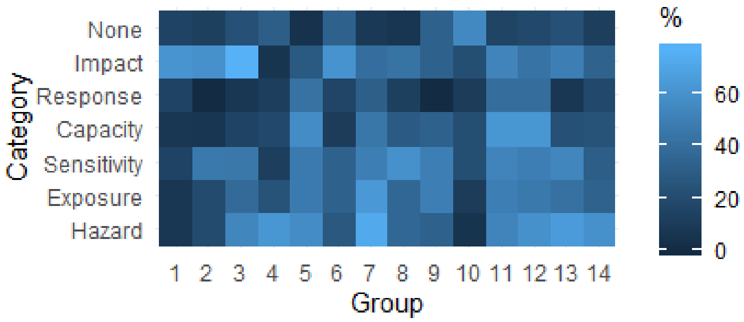

Figure 5. Heatmap of groups and resilience categories. Cell color scale of row i and column j corresponds to the percent of documents in each group j that address resilience category i.

The overall distribution of resilience categories is not surprising given the general state of adaptation practice (Figure 6). Hazards and impacts to natural systems have been most identified, followed by exposure and sensitivity. As not much adaptation has occurred, capacity and response measurements are less frequent. A few groups, such as 10, have a high number of documents in which no resilience category was found. Overall, about 20% of documents had no resilience category, as the information provided was judged to be unable to lead to the development of a resilience indicator. Of these, about half were non-peer reviewed reports, with the rest being either webpage summaries or presentations.

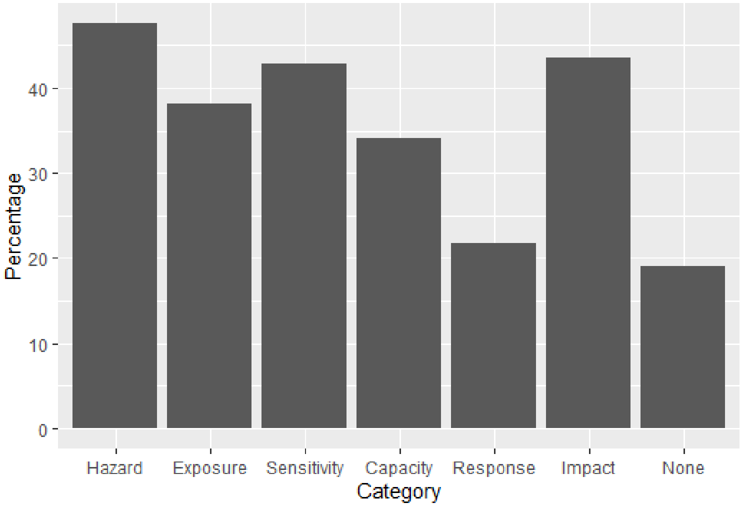

Figure 6. Percentage of documents that address each resilience category.

The types of information found in the documents are a good proxy for the readiness of indicator production. Over half of the documents had defined indicators with backing data, leaving the other half with a dataset with no indicator framework, an indicator framework with no data, or neither (Figure 7). This indicates that, overall, there is a long way to go to develop coastal resilience indicators for Maryland and the Chesapeake Bay region. However, development is not homogeneous across document types and resilience categories.

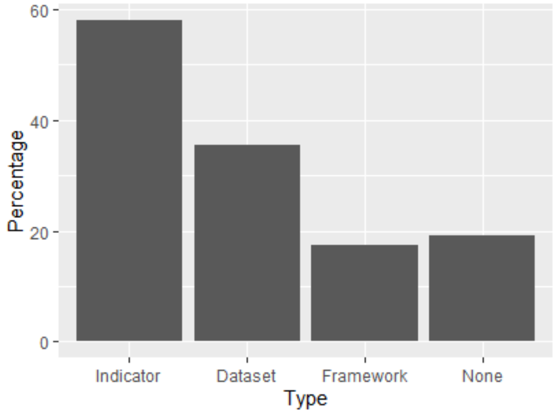

Figure 7. Percentage of documents by type of information. Documents may have more than one type of information.

Figure 8 gives a sense of the readiness of each group. Ideally, most if not all documents in each group would be ones with indicators, such as groups 1, 2, 8, and 13. Groups 1 and 2 are mostly impact-oriented measures of aquatic ecosystems and water quality, while the others are spread more evenly across resilience categories and climate themes. The second best would be where indicator and datasets are the top two: groups 4, 7-9, 11-14. Group 4 focuses on hazards of sea level rise, while groups 11 and 12 are more comprehensive planning documents. The remaining groups are more underdeveloped but in different ways. For example, group 5 consists mostly of indicator frameworks without quantifiable data, while group 10 is heavily composed of documents with no framework or data.

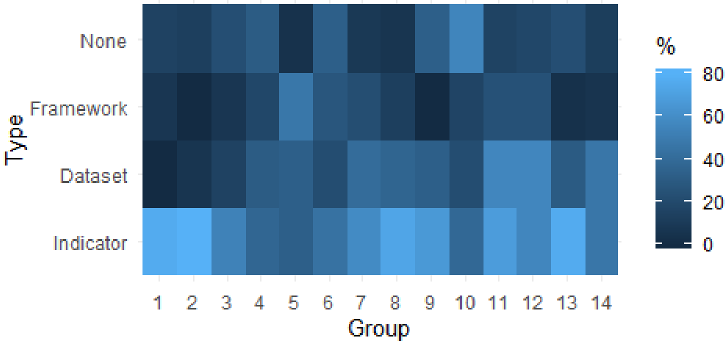

Figure 8. Heatmap of groups and types of information. Cell color scale of row i and column j corresponds to the percent of documents in each group j information type i.

Discussion

Across all climate themes and resilience categories, our document assessment has shown that much work remains in order to develop a comprehensive resilience indicator set for coastal resilience in Maryland and the Chesapeake Bay region more broadly. In particular large gaps exist for resilience indicators pertaining to capacity and response, which are key adaptation actions that represent how the system is changed to increase resilience (Figure 1). In contrast, hazard and impact indicators are better represented as indicators, datasets, or frameworks, which are necessary but not sufficient information to both understand the climate impact challenges and to assess, over time, the changes that have occurred as a result of actions taken. Depending on the specific adaptation challenge, even if resilience information is relatively well-represented within this document analysis, it is likely that the information will need to be customized and contextualized or the right representation of the information may not be available for a particular problem.

In particular, for the Chesapeake Bay region, there is an unsurprisingly strong representation of information related to sea level rise, water quality, flooding, and aquatic ecosystems. This is the result of a regional focus on “saving the bay” to improve the health of the Chesapeake Bay estuary [92]. Additionally, there has been an increase and more visible impacts of “sunny day or nuisance flooding” that occurs during high tides on days without precipitation. For example, Annapolis, MD has had a 925% increase in nuisance flooding days since the 1960s [93], which causes flooding of streets and businesses in major cities such as Annapolis [94] and has been a major focus of regional planning efforts (e.g., Weather it Together) [80].

Of the themes represented, climate change and health impacts had the fewest number of documents in our sample. Human health impact of climate change is a growing area of concern and require specific adaptation actions to minimize mortality/morbidity (e.g., high heat interventions such as cooling stations or increased awareness of heat stress symptoms by healthcare providers). As a result, there are tremendous research opportunities to especially understand regional responses (Figure 5) [95] and develop indicators [96].

Of the themes identified, it was notable that the only ones that are linked directly to human systems are the economy, health, and built environment (Figure 3). Notably, other social dimensions that are useful for more robustly understanding the resilience of a community were limited in their representation, similar to the findings from Molino et al. [97]. The lack of information to develop social and cultural indicators limits our ability to more comprehensively assess the effectiveness of adaptation actions for coastal communities, economies, policies, and behaviors, including the ability to understand whether adaptation actions are reducing existing social inequities [98–100]. This is in part because the data collection needed to have robust representations and trends of these social dimensions are far behind our data collection of biophysical systems [100], especially for factors that are not collected as part of the US Census Bureau data products [101] and which involve diverse data types and the sharing of human subjects information [102].

Finally, in assessing the information landscape for resilience, there may be a reasonable amount of information that can be customized to understand various climate hazards and impacts. However, it is unlikely that enough information exists to do so for responses [103]. This may lead to problems in developing usable indicators because understanding the adaptation responses adopted in a region is critical. In addition, it is necessary to have information and indicators that allow an assessment of a range of adaptation action types, including those that are beyond built and natural infrastructure projects [15]. As a result, to both understand the adaptation actions that are being implemented (process indicators) and the effectiveness of such response actions, more comprehensive data collection of adaptation actions beyond planning reports are necessary [1,100].

Overall, this review highlights that for climate adaptation, there are specific areas, such as aquatic systems, where there are more well-developed information and other areas, such as social and cultural information, that are limited for the Chesapeake Bay region. Even for information sources that are well developed, there is a need to develop datasets and frameworks into indicators that would assess the activities and effectiveness of adaptation and resilience actions for both specific projects as well as for multiple projects in communities. Thus, context matters and it will be necessary to translate such information, in collaboration with stakeholders, into usable indicators for a particular location and adaptation decisions in order for it to appropriately measure the process and effectiveness of adaptation [104,105]. Such investments in process and effectiveness indicators are critical to evaluating whether we are making good adaptation decisions or whether different or more aggressive actions are necessary.

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Technical Appendix

In order to explore document/effect clustering, climate effects are coded into a binary matrix with each row corresponding to a document and each column corresponding to an effect. For a matrix element (i, j), a value of 1 indicates that document i addresses effect j, while a value of 0 indicates that document i does not address effect j. Using the *hclust* function from the *stats* R package, an agglomerative hierarchical clustering algorithm is then used to partition the documents into similar clusters in a way that aids descriptive analysis: documents in a cluster are similar enough to each other to be summarized together and clusters are dissimilar enough to highlight important differences.

Agglomerative hierarchical clustering works by first calculating the distance among all initial nodes (i.e., documents). Measuring distance is specific to data type and the nature of the cluster analysis. Euclidean distance is one of the most popular options, however it is inappropriate to use for binary data. As a result, we use the asymmetric binary distance metric, which is a common choice for our data format. After calculating distance, similar nodes with small distance are merged together in small clusters.

As the algorithm steps forward, it iteratively considers which clusters to merge together until it reaches one large cluster whose membership size equals the original number of nodes. The metric used to measure the similarity of clusters is another choice that has to be made based on data type and analysis goals. The *hclust* function offers several options for this cluster linkage metric. To choose an appropriate linkage metric, we cluster the data using each metric and compare the resulting agglomerative coefficient, which measures the quality of the hierarchical cluster structure. At a value of 0.99, the Ward linkage method yields the highest agglomerative coefficient; consequently it is used in the subsequent analysis.

While clustering algorithms assign cluster membership, they do not choose the optimal number of clusters. This is done by reference to a cluster validity index, of which there over 30 available. Comparative studies of metric performance have shown that a small subset tends to perform well across a range of data structures [37–39]. For the purpose of this analysis, we utilize one of these indices, the Calinski-Harabasz (CH) index, calculated by the *NbClust* R package. It is an internal clustering validation measure that calculates the ratio of between- to within-cluster variability. Since an ideal number of clusters would have larger between-cluster variability and smaller within-cluster variability, useful clusters can be found where the CH index value peaks. To corroborate the reasonableness of the clusters chosen by CH index, we also choose the number of clusters by visual inspection of the clustering dendrogram.

The CH index shows peaks at 4, 7, and 14 clusters, with 4 clusters being the global maximum (Fig A1). This indicates that these cluster configurations have relatively high dissimilarity among clusters and high similarity among cluster members.

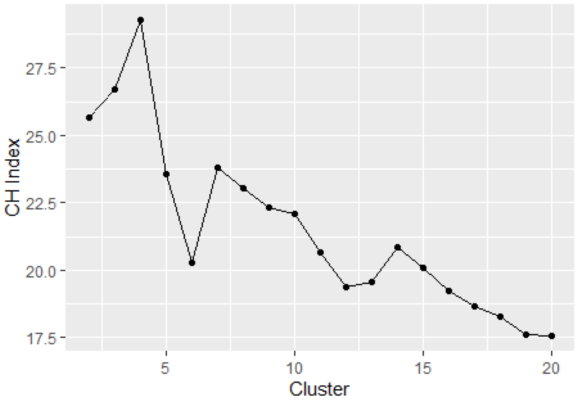

Figure A1. Calinski-Harabasz (CH) index

The composition of the four cluster grouping is shown below in FigureA2, where each row consists of binary cells indicating whether an effect is present (light blue) or not (dark blue) for one document. The top level split in the attached row dendrogram differentiates documents that almost entirely focus on aquatic ecosystems and water quality from documents that have a mix of other foci. Interpreting the content of the other clusters, especially the largest cluster, is somewhat difficult because of their diversity. Therefore, exploring the 7 and 14 cluster groupings is necessary.

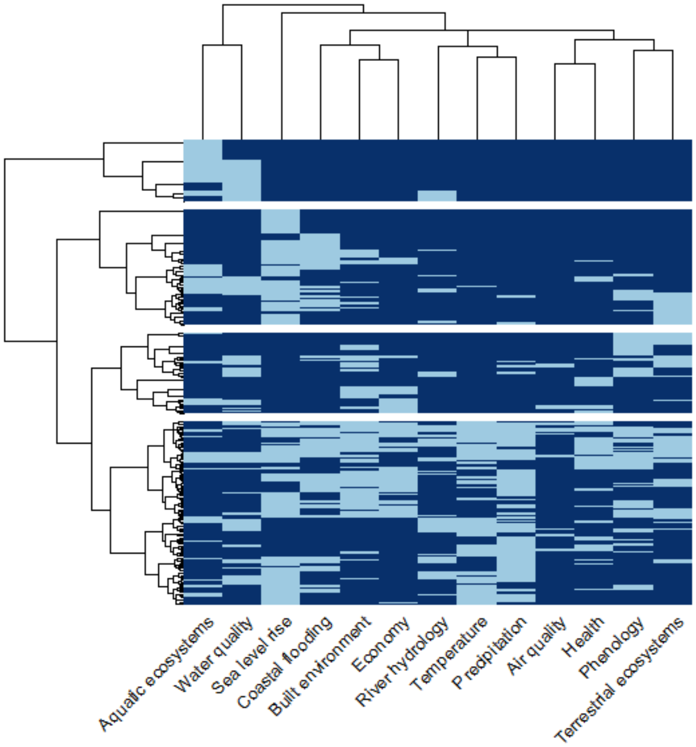

Figure A2. Heatmap with attached dendrogram of four-cluster grouping. Rows (unlabeled) show what effects (column headers) each document contains; a light blue cell indicates the presence of an effect. Clusters are connected to the row dendrogram of the hierarchical cluster structure, while effects are ordered according to the column dendrogram.

The 7-cluster grouping further refines the more homogenous clusters, highlighting documents that (i) address only aquatic ecosystems, (ii) have a strong focus on aquatic ecosystems and water quality, and (iii) address only sea level rise. However, other clusters are still difficult to interpret, necessitating the 14-cluster group.

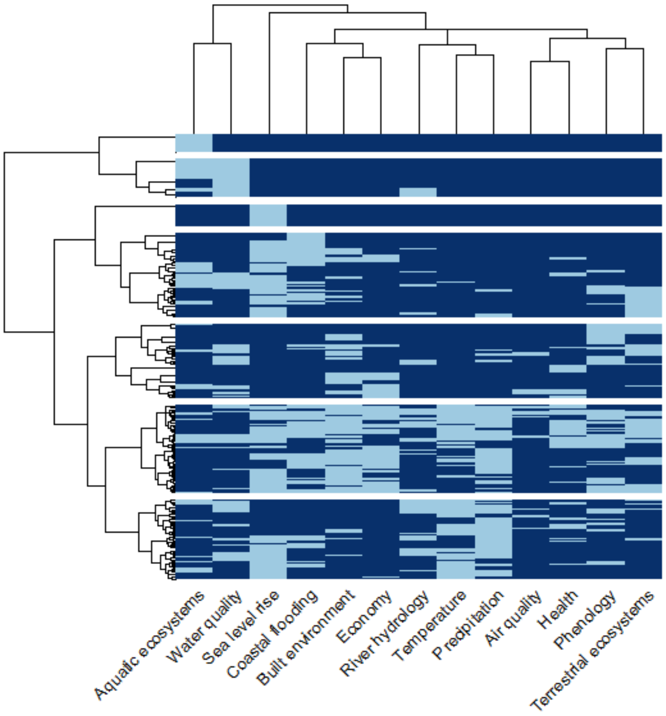

Figure A3. Heatmap with attached dendrogram of 7-cluster grouping. Rows (unlabeled) show what effects (column headers) each document contains; a light blue cell indicates the presence of an effect. Clusters are connected to the row dendrogram of the hierarchical cluster structure, while effects are ordered according to the column dendrogram.

The 14-cluster grouping both identifies other homogenous clusters and further refines the more diverse clusters into interpretable groups. The higher number of groups also highlights which effects are more likely to appear together, which is shown by the column dendrogram. For example, aquatic ecosystem and water quality effects are most likely to appear together as they are joined by a top-level link in the column dendrogram. Other pairings include (i) built environment and economy, (ii) temperature and precipitation, (iii) air quality and health, and (iv) phenology and terrestrial ecosystems.

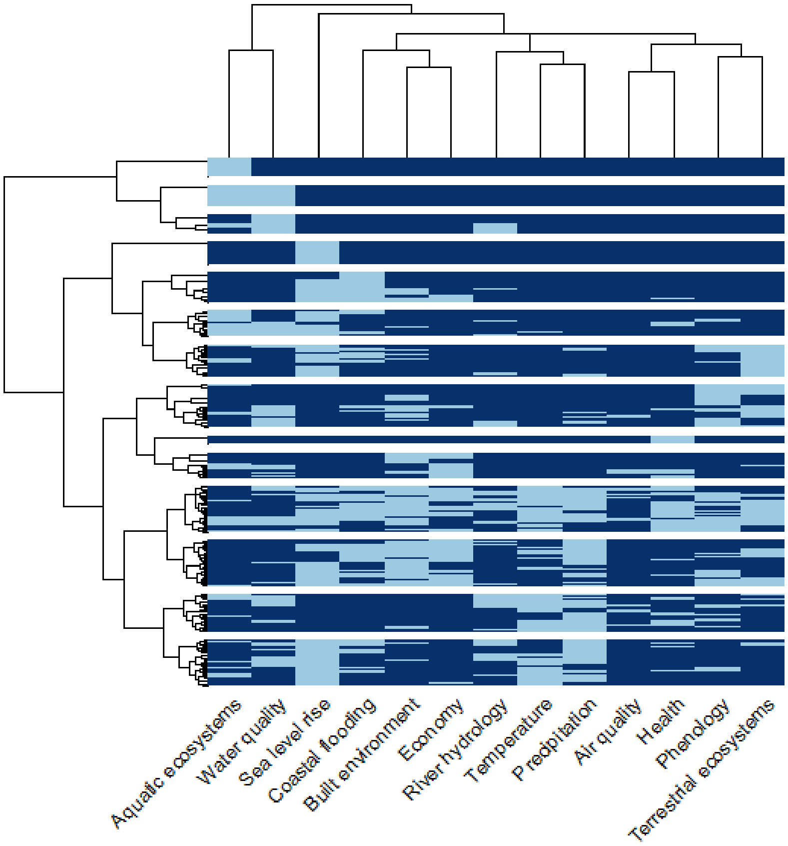

Figure A4. Heatmap with attached dendrograms of 14-cluster grouping. Rows (unlabeled) show what effects (column headers) each document contains; a light blue cell indicates the presence of an effect. Clusters are connected to the row dendrogram of the hierarchical cluster structure, while effects are ordered according to the column dendrogram.