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Considering scale and scaling for vulnerability and adaptation studies in the water sector

Case studies in four geographies

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Considering scale and scaling for vulnerability and adaptation studies in the water sector

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Climate change is impacting the hydrologic cycle globally. Understanding how these changes may impact water related resources and hazards are priorities for development and sustainability initiatives. Frequently these concerns are addressed through vulnerability and adaptation studies. Scaling drives much of scientific analysis. It is how we move from identifying individual factors and interactions within a system to modeling the system itself. Intuitively, exploratory data analysis usually begins with a broader collection of data in an effort to recognize patterns and processes. As understanding of these patterns and processes progresses, we maximize efficiency by isolating and including only the most necessary factors in models to predict change.

This project explores data quality and relevance for vulnerability and adaptation to climate change studies framing the discussion in the context of scaling limitations and opportunities. Four geographies are selected as case studies for their distinct geologic and hydrologic conditions: a Small Island Developing State, a delta, an estuary and a mountainous region. Common disciplinary approaches utilized for vulnerability and adaptation assessments including remote sensing, modeling, participatory social research and hybrid approaches, are compiled for each region. Within each, the quality and relevance of data resources utilized for addressing common water sector concerns from an environmental hydrology perspective is discussed.

Results recommend that consideration of scaling progression through the stages of scientific analysis can be used conceptually and pragmatically to guide data collection and analysis irrespective of disciplinary approach. For example, statistical analyses of point-source data of pollution and other water quality parameters have successfully supported the management of estuaries where modeling approaches are unrealistic (D'Elia et al. 2003; Bianchi 2013). Reconstruction of historical profiles of climate and climate related hazards through social approaches has helped to inform disaster risk reduction activities and reconstruct past climate in data scarce regions (Dixit et al. 2009; Nadeem et al. 2009; Opitz Stapleton and MacClune 2012; Birk 2014).

The environmental processes relevant to vulnerability and adaptation assessments should be placed at the heart of adaptation policies for hydrological events. Different scientific resources and tools are needed to characterize and monitor hydrologic processes to support science-based management decisions. We highlight exemplary basic hydrologic concerns for four geographies to show the particularities and needs that arise from them. Recommendations for informing knowledge information centers to assist users with vulnerability and adaptation studies are provided.

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1 Introduction

1.1 *Vulnerability and Adaptation*

Vulnerability and adaptation are terms that generally define susceptibility and adjustment to the damaging effects of a hazard, respectively. However, there are no single agreed upon definitions for these terms. For this project, the terminology utilized by the United Nations International Strategy for Disaster Reduction (UNISDR) and the Intergovernmental Panel on Climate Change (IPCC) are provided. UNISDR defines vulnerability as “the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard” and adaptation as “the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (UNISDR, 2009). The IPCC's Fifth Assessment Report (AR5) defines vulnerability as “the propensity or predisposition to be adversely affected” and adaptation as “the process of adjustment to actual or expected climate and its effects” (IPCC, 2014). Definitions for vulnerability and adaptation throughout individual analyses included in the case studies vary, but agree conceptually with these definitions.

1.2 *Water sector concerns*

Climate change is likely to significantly increase human exposure to droughts and floods globally. As discussed in Miller and Belton (2014) and presented in the fifth report of the IPCC working group II, global warming will effectively accelerate the water cycle, increasing the likelihood of extended dry periods or periods of heavy rainfall (see Allen and Ingram 2002, Dai 2006, Bates et al 2008, Lenderink and Van Meijgaard 2008) and driving changes in patterns of atmospheric circulation that might alter regional runoff patterns and probabilities of hazardous weather events (see Kundezewicz et al 2007, Bates et al 2008). Similarly, the influence of climate change on water resource concerns such as water availability and water quality is also brought into question.

1.3 *Scale and scaling*

Marceau (1999) defines a metaphor for scale that can easily be envisaged across disciplines; a lens or measuring tool through which a phenomenon or vulnerability is viewed or perceived. Scaling refers to the transfer of information between different types and dimension of scale. Transferring information between the observational-, modeling- and policy- scales involves scaling, as does the transfer of information between spatial and temporal scales.

Choosing the appropriate scale for vulnerability and adaptation to climate change is not easily accomplished; no single scale is the most appropriate for studying a problem, especially one that involves social, environmental, governance and other factors. Instead, focusing on what processes, mechanisms and patterns relevant to the environmental phenomenon in question that can be identified, monitored, and predicted at a given scale may be more productive.

Figure 1 (below) shows a schematic of basic components or elements of scaling. While scientific inquiry does try to follow a certain progression, for example, from exploratory data analysis, to experimental design, field-testing, monitoring and modeling, it should be noted that this is not always a linear or sequential process.The inner loop of **Figure 1** recommends potential components or elements along a scaling progression. The outer loop recommends tools that are commonly used in isolation or in conjunction to progress along the scientific pathway. Vulnerability and adaptation to climate change are intrinsically complex, so scaling elements and tools can assist in working through that complexity.

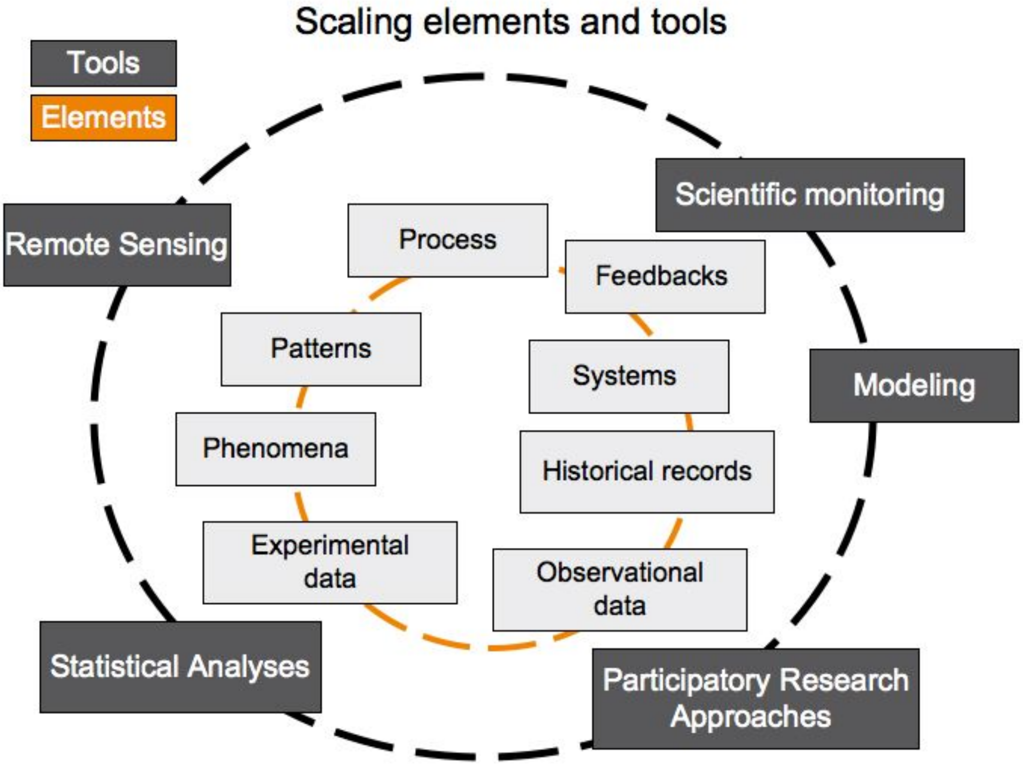

Figure 1 : Elements or components of scaling (inner loop) and tools and methods commonly used for monitoring vulnerability at different scales (outer loop).

1.4 *Description of project methods*

In the first stage of this project a review was conducted to compile and assess the quality and relevance of data resources for vulnerability and adaptation studies to climate change. The review could not be comprehensive, as the high volume of datasets available globally precludes this. To address this problem, a set of criteria were established to prioritize data resources based on: (i) global, free access to the data from well-established resources (e.g., long standing scientific, government, or non-profit organizations with a good track record for data maintenance) (ii) documented validation of data products (iii) availability of support from scientific community or data resource providers (e.g. through training, online user community groups, or other support methods) and (iv) ease of use (e.g. level of scientific knowledge required to utilize data resources). When it was not possible to meet all criteria, for example, in very data scarce regions, the best-fit resources were highlighted.

The primary objectives of the data review were to: (1) identify potential resources and tools for inclusion in future knowledge information centers, hosted by institutions such as Climate Services Center, and (2) to inform on latest data resources available for the companion paper in the second stage of the project. **Table 1** (below) shows examples of some data resources identified during the data review available globally.

Table 1: Examples of global, freely available data resources and tools useful for environmental aspects of vulnerability and climate change studies.

Geography or coverage	Product description	Accessibility
Global (Land)	Global land cover (30 m, annual to semi-annual). Sources: United States Geological Survey; European Space Agency. Global deforested area (30 m, 2000-2012). Source: Hansen et al. (2013) available through Google Earth Engine. Atlas of the Cryosphere (basemaps of glacier area, glacier extent, permafrost extent/type). Source: National Snow and Ice Data Center. HydroSHEDS and Hydro1k (global river channel network data and hydrological network data, respectively. Consistent global coverage of topographically derived hydrological data such as river and stream networks, drainage basins, flow direction.) Source: United States Geological Survey.	All satellite products mentioned are freely available online and can be utilized with freely available software online. Scientific studies have validated the products and validation information is available.
Global (Social, economic)	Global Rural Urban Mapping Project (GRUMP) (eight global datasets population count, density, urban settlements/extent for 1990, 2000, 2005). Source: SocioEconomic Data Applications Center (SEDAC).	SEDAC hosts a variety of products for free including maps of IPCC outcomes, hazard maps, infrastructure and population data. Online visualization capabilities.
Global (Oceans)	ReefBase and ReefGIS (global information system for coral reefs; indices of coral bleaching and sea surface temperature; access to related academic literature free of charge; access to biodiversity and other datasets reported though online community). Source: World Fish Center.	Free online access with registration. GIS mapping capabilities. Access to relevant scientific literature and publications. Information on product validation available.
Global (Biodiversity)	Ocean Biogeographic Information Center (OBIS USA). Marine biological occurrence data. Source: United States Geological Survey. NatureServe Climate Vulnerability Index (tool to help idenfiy vulnerability of plant and animal species.) Source: NatureServe.	Free online access to biodiversity data, ability to contribute user data, help with determining vulnerability using NatureServe program.

Figure 2 (below) illustrates how results of the project could be integrated into a knowledge information center. Ideally, practitioners and scientists conducting vulnerability and adaptation studies would have access to a knowledge information center containing (i) meta-data, (ii) guidance for method selection, (iii) reproducibility assurances (e.g. guidance on data retrieval, data processing, validation), (iv) access to scientific knowledge/training where necessary and (v) a forum for reporting results to contribute to the evidence base.

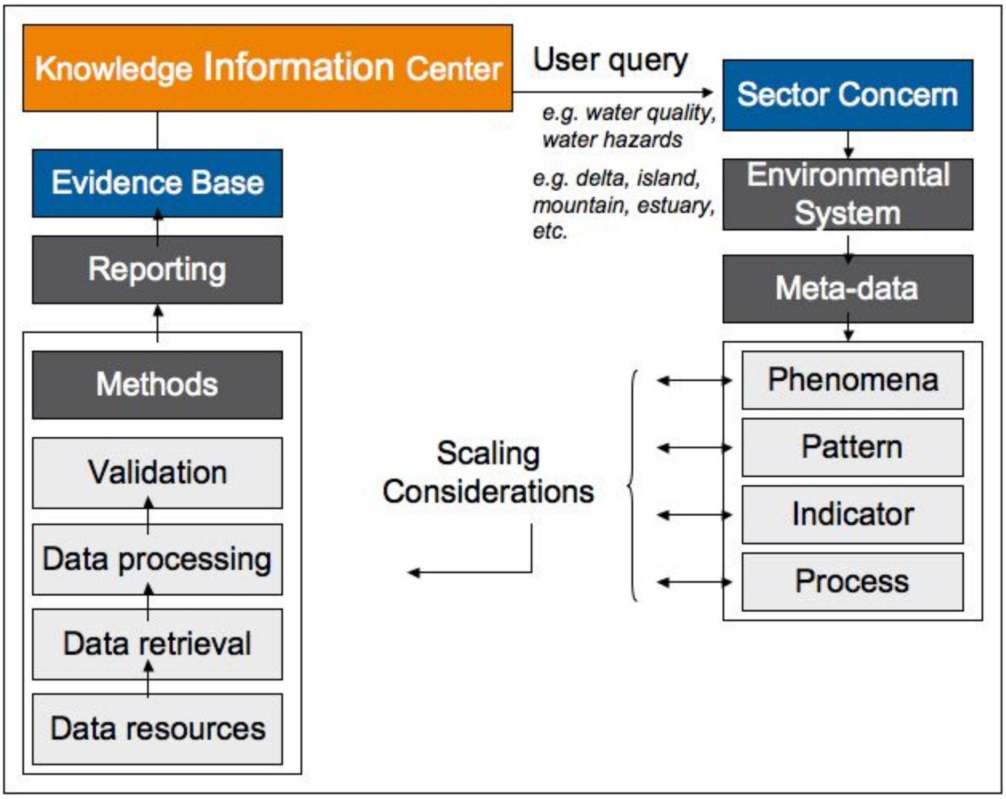

Figure 2: Schematic for key elements of a knowledge information system for studies on vulnerability and adaptation to climate change.

In stage two of the project an academic article was written on the topic of assessing data quality and relevance for vulnerability and adaptation to climate change in the water sector (Shreve, Máñez Costa and Kelman, Submitted). Four case study geographies were selected because of their distinct geologic and, hence, hydrologic, conditions: a Small Island Developing State (SIDS); a delta region (Vietnamese Mekong Delta, VMD); an estuary (Chesapeake Bay estuary, the Bay); and a mountainous region (Hindu Kush Himalaya, HKH). Case study site descriptions are provided in the following section. Key results from the study are highlighted here and more detail can be found in the companion article.

2 Case Studies

2.1 *Small Island Developing States*

Small Island Developing States (SIDS) are low-lying coastal countries that share similar sustainable development challenges such as growing populations and limited natural resources, vulnerability to external shocks, frequent occurrence of natural hazards and other stressors. Some distinctive features of hydrology of SIDS include: (i) absence of rivers and river basins in many atolls, reef islands and smaller oceanic islands and (ii) freshwater lenses. When rainfall recharge is sufficient on oceanic islands, the result is a freshwater lens, whereby freshwater exists as a lens above seawater due to density differences (Morgan and Werner, 2014).

Freshwater lenses are primarily vulnerable to climate change due to: (i) the low topographic relief of oceanic islands, which leads to flat hydraulic gradients and high susceptibility to land surface inundation by the ocean, (ii) an often thin freshwater zone, which increases the impacts of drought and excessive pumping on the lens, (iii) and heavy reliance of local communities with few alternative water sources (White et al., 2007; White and Falkland, 2010 as cited in Morgan and Werner, 2014).

The Maldives was selected as a focus region for SIDS, as its heterogeneous composition facilitates discussion of needs that may occur in different SIDS. Maldives is composed of a more than 1,100 small islands and atolls located in the Indian Ocean to the west of the southern coast of India.

2.2 *Vietnamese Mekong Delta*

The Mekong Delta begins in Phom Penh, Cambodia and a majority of the delta is located in southern Vietnam. Coastal deltas have unique geomorphic and hydrologic features. Upstream land cover and land use, in addition to these propertie locally, influence overland flow and river discharge. Where the river meets the ocean, complex mixing processes occur. Climate change may impact physical hydrology in Can Tho, e.g. through changes in rainfall and precipitation, as well as exacerbating development concerns, e.g. water quality and availability and water related hazards.

2.3 *Chesapeake Bay*

The Chesapeake Bay (the Bay) is located in the mid-Atlantic region of North America and is among the world's most productive estuaries (Kane, 2013). Estuaries, not unlike coastal deltas, are systems with complex terrestrial and marine processes. Estuarine ecosystems are vulnerable to human activities that lead to water pollution, especially as it pertains to nutrient pollution and sedimentation. For example, increased nitrogen concentrations from agriculture and increased sediment load due to river dredging. Estuaries are particularly vulnerable to climate change because they can respond to three primary types of forcing: (1) streamflow quality and quantity; (2) air-water fluxes of carbon dioxide, heat, freshwater (i.e. evaporation and precipitation) and momentum (i.e. wind stress); and fluctuations in sea-level and other ocean properties (Najjar et al., 2010). Similar to the VMD, the Bay region is impacted by anthropogenic and climatic impacts upstream from, as well as within, the watershed.

2.4 *Hindu Kush Himalaya*

The Hindu Kush Himalaya (HKH) region is not a precise geographic qualifier. For the purposes of this project, the International Centre for Integrated Mountain Development's (ICIMOD) definition of the HKH to include the Karakorum, the Pamir, and other neighboring mountain ranges, is adopted. ICIMOD's definition was selected because of the extensive amount of work the organization has conducted on vulnerability and adaptation to climate change within the HKH, with partners from academia, NGOs, non-profit organizations and governments.

The HKH houses parts of ten of the major rivers in Asia (Bandyopadhyay, 1996) and both slow onset and fast onset water related hazards are common. Flash floods, seasonal floods and Glacier Lake Outburst Floods (GLOFs) are common in the region, as well as drought. Thus understanding what impacts climate change may have on water hazards in the region is of special interest for development and Disaster Risk Reduction initiatives.

3 Key results by geography

3.1 *Small Island Developing States*

In situ studies such as isotopic tracers and hydro-chemical analyses are useful for measuring rainfall recharge to freshwater lenses in SIDS (e.g. Vacher and Ayers 1980; Jones and Banner, 2003; Najeeb and Vinayachandran 2011; Chattopadyay and Singh 2013). Spatial and temporal scale for these studies generally ranges from 10s-100s of meters and encompasses seasonal rainfall extremes. In situ studies have shown the importance of island geometry on freshwater lenses and the role of precipitation in saltwater intrusion into freshwater lenses (**Table 2**). The results are significant because they demonstrate levels of heterogeneity and specificity not considered by most hydrologic or climate models, specifically, precipitation is not usually considered a key factor impacting saltwater intrusion for small islands

(Chattopadhyay and Singh 2013) and basic hydrologic relationships governing freshwater lenses do not consider the impacts of the irregular geometry of reef islands or atolls (Najeeb and Vinayachandran 2011).

Remote sensing and Geographic Information Systems (GIS) are commonly applied for quantifying shoreline extent and shoreline change (e.g. Ford 2013; Birk, 2014). Hydrologic and climate modeling is less extensive on SIDS compared to the other case study geographies. Local estimates of sea-level rise require proxy data (Gehrels 2010) or semi-empirical models (Ramhstorf 2010). Sediment cores and fossil dating, part of the proxy analysis for local sea-level change, can be used to inform historical analysis.

Table 2: modified after Shreve, Máñez Costa and Kelman (Submitted). Comparison of data resources utilized for vulnerability and adaptation assessments for SIDS.

Geography	Scientific in situ or experimental studies	Models	Geospatial Analyses	Social or Participatory Research Approaches	Water Sector: key concerns; hydrologic components; spatial & temporal scales
Lakshadweep Western Indian Ocean	Hydro-chemical analysis to inform water budget (Chattopadhyay and Singh, 2013)[1]				Indicators of water availability and quality; rainfall recharge; island wide; current time scale[1]
Maldives, Indian Ocean	Proxy measures for sea-level change (Mörner, Tooley and Possnert, 2004)[2]	Regional climate change models & impacts under 2°C warming scenario (Jacob, 2014)[3]		Political mal-adaptations due to climate change discourse, (Kothari, 2013)[4]	Water quality and availability, sea-level change; island wide; historical analysis, past 5,000 yrs[2] Water availability and water quality; temperature, precipitation, sea-level change and predicted impacts; island wide; 10s-100s years into the future[3] Water management and development; sea-level change; island wide; recent decades[4]
Atolls/small oceanic islands (general)		Seawater Intrusion Index using steady state analytic model (Morgan and Werner, 2014)[5]	Shoreline change and spatial delineation of shoreline (Ford, 2013)[6]		Water availability and water quality; rainfall/recharge; island wide; current time scale[5] Coastal management; sea-level change, erosion/accretion; recent decades[6]

3.2 *Vietnamese Mekong Delta*

Modeling at a variety of spatial and temporal scales is more common in Can Tho, VMD, compared to SIDS. Intensive modeling efforts at the local scale, such as coupling hydrologic-, urbanization- and climate-models for 3D inundation modeling (e.g. Huong and Pathirana 2013) provide detailed estimates of potential impacts of sea-level change. Other studies utilize larger spatial scale Global Climate Model (GCM) results for sea-level rise and GIS systems to refine potential climate change impacts by land use (Wassman et al 2004). Hybrid natural and social-science approaches, for example, Trinh et al. (2013) couple water sampling with participatory research to devise pollution management strategies (**Table 3**).

Table 3: modified after Shreve, Máñez Costa and Kelman (Submitted). Comparison of data resources utilized for vulnerability and adaptation assessments for Can Tho City, Vietnamese Mekong Delta (VMD).

Geography	Scientific in situ or experimental studies	Models	Geospatial Analyses	Social or Participatory Research Approaches	Water Sector: key concerns; hydrologic components; spatial & temporal scales
Can Tho, VMD	Climate Change Adaptation Indicators (Trinh et al., 2013)[1]	Coupled simulation models (Huong and Pathirana, 2013)[2]		Hazard, Capacity and Vulnerability Assessment (ACCCRN, 2011)[3] Climate change adaptation at the household scale (Birkmann et al. 2010)[4]	Water quality and water management, CCA scenarios; pollution; city scale; current time scale[1] Flooding, urbanization and climate change; sea-level rise, inundation, precipitation; city scale; decadal timeframe; forward looking[2] Water availability and quality, water hazards; city scale, current time scale and near-term planning[3] Water availability; household scale, adaptation measures to flooding; river level; recent decades[4]
Mekong Delta (general)			Floodplain mapping and characterization (Syvitski et al., 2010)[5]		Flooding; global, daily mapping of floodplains, ~30 yrs of data to present[5]

3.3 *The Chesapeake Bay*

Scientific monitoring of water quality parameters such as Total Nitrogen (TN) and suspended sediment have played a supporting role in water resources management (D'Elia et al. 2003). In situ studies such as sediment core sampling provide a historical record that has been linked to satellite estimates over recent decades to better understand changes in water quality over time and the potential impacts of climate (**Table 4**). Larger scale GCMs are useful for predicting how habitat conditions may change for marine species, which can be used to guide experimental research and monitoring. However, these studies are not intended or suited for local management and monitoring objectives.

Table 4: modified after Shreve, Máñez Costa and Kelman (Submitted). Comparison of data resources utilized for vulnerability and adaptation assessments for the Chesapeake Bay.

Geography	Scientific in situ or experimental studies	Models	Geospatial Analyses	Social or Participatory Research Approaches	Water Sector: key concerns; hydrologic components; spatial & temporal scales
Chesapeake Bay (subwater-shed)	~ 300 sediment cores analyzed providing ~12,000 yr history (Kemp et al., 2005)[1]		Water sampling, RS/GIS analysis of land use change and impacts on water quality (Kaushal et al., 2008)[2]		Water quality; hypoxia and euthrophication; watershed; historical analysis[1] Water quality, land cover change and water quality, climate; Maryland; recent decades[2]
Chesapeake Bay (watershed)	Ecological approach to defining vulnerability (e.g. 3 principal components: sensitivity, exposure and adaptive capacity) (Kane, 2013)[3]		Remote sensing measures of: chlorophyll-a (chl-a), Total Nitrogen (TN); inter-annual variability (Chesapeake Bay Remote Sensing Program, undated)[4]		Water quality, habitat restoration, climate change; proxies/indicators of habitat quality; watershed; current time scale to future planning (decadal)[3] Water quality; watershed scale; recent decades[4]
Marine and coastal environments, North America (general)		Interprets climate model results for marine and coastal environment (Scavia et al., 2002)[5]			Water quality (temperature, habitat suitability); watershed; 10s-100s of years, forward looking[5]

3.4 *Hindu Kush Himalaya*

Global climate change initiatives may influence the data resources and tools utilized for planning. One example is the use of 'risk-based' modeling for flood hazard management adopted by the European Union (EU). Frequently development funders, for example, the United Kingdom's Department For International Development (DFID), will encourage a similar approach be adopted by funding recipients (Optiz Stapelton and MacClune 2012). Of all the case studies examined, the HKH is likely best-suited for a modeling approach. While modeling should not be viewed as a panacea, as complications arise due to the availability and quality of local meteorological data required for downscaling techniques, as well as other limitations regarding future management and urbanization, modeling may provide pragmatic information for planners in this geographically large, data scarce region. Based on similar principles, remote sensing, because of its ability to cover large geographic regions on frequent time intervals, has shown very useful for water hazard monitoring in the HKH (**Table 5**). Traditional knowledge of water resource management and water hazards has yet to be included directly in monitoring and Disaster Risk Reduction (DRR) initiatives, however the potential to do so exists.

Table 5: modified after Shreve, Máñez Costa and Kelman (Submitted). Comparison of data resources utilized for vulnerability and adaptation assessments for the Hindu Kush Himalaya (HKH).

Geography	Scientific in situ or experimental studies	Models	Geospatial Analyses	Social or Participatory Research Approaches	Water Sector: key concerns; hydrologic components; spatial & temporal scales
India		EU High Noon Project (Moors et al. 2011) [2]			Water hazards and water management; precipitation, temperature, river flow; river basin; 10s-100s years, forward looking[2]
Pakistan				Assessing traditional knowledge of water hazard and water resource management (Nadeem et al., 2008)[3]	Water availability and water hazards, EWS; observational analysis of environment characteristics; river basin; historic-present day[3]
Nepal				CCA strategies for water and perceptions of risk (Dixit et al., 2009)[4]	Water hazards and risk perceptions; flooding, drought; community scale[4]
Hindu Kush Himalaya (general)			HKH HYCOS: satellite flood monitoring (Shrestha et al., 2012)[5] Global Landslide Susceptibility (Hong, Adler and Huffman, 2007)[6]	Rapid rural appraisals: Interview questions regarding climate history (Su et al., 2013)[7]	Water hazards and EWS; precipitation; river basin; current time scale[5] Water related hazard (landslides), EWS; terrain and slope angle; global; one-time study, past decade[6] Loss estimates from drought/flooding; flooding, drought; sub-basin; recent decades-present day[7]

Table 6 summarizes variables and recommended methods for monitoring water sector concerns for generalized geographies. Precipitation is an important process for monitoring across case study geographies, though relevant to different aspects of water sector concerns for each. In SIDS, precipitation, ideally gauged from local meteorological stations, is needed for

assessing rainfall recharge to freshwater lenses and saltwater intrusion rates. In estuaries and deltas, precipitation is important for water quality, flooding and saltwater inundation. In mountainous regions such as the HKH, precipitation is also an important process to monitor in relation to water hazards such as drought and flooding. Local meteorological data of precipitation is always beneficial, as precipitation is naturally variable. Satellite estimates provide global coverage of precipitation, however they are better suited for larger, more homogenous geographic regions, as the spatial resolution of these products (e.g. 100s of kilometers) may not capture local variability. Sea Surface Temperature (SST) can be utilized to generate metrics of coral bleaching and ocean acidification which may be important for assessing vulnerability and adaptation of marine environments for SIDS. Similarly, remote sensing data of chlorophyll-a concentration can be applied for monitoring spring algal blooms associated with eutrophication in deltas and estuaries.

Table 6: modified after Shreve, Máñez Costa and Kelman (Submitted): Summary of key components for measuring and monitoring water sector concerns.

Geography	Phenomena, pattern, process or indicator	Data resources for monitoring
Small oceanic islands, atolls or reef islands	Rainfall recharge to freshwater lenses	Meteorological stations needed for daily observations; satellite data too coarse spatially; isotopic tracers useful for rainfall recharge, as are steady state analytic models (first-order estimate)
	Sea-Level Rise (SLR)	Semi-empirical model and in situ measures for local estimates
	Coral bleaching, ocean acidification, Sea Surface Temperature (SST)	Ocean acidification, coral bleaching indices from remote sensing; remote sensing of sea surface temperature
Small mountainous islands	Deforestation, precipitation	In situ measures best for water quality; remote sensing may be useful for flash flood/landslide susceptibility models; remote sensing of deforestation on yearly time-step may be useful
Coastal deltas and estuaries	Spring algal bloom, Total Nitrogen (TN) concentration in water	In situ and remote sensing measures useful, sediment cores for historical record
	Sea-Level Rise (SLR)	Global Climate Model (GCM) and Regional Climate Model (RCM) estimates; semi-empirical models for local estimates
	Precipitation	Meteorological stations and satellite data
Mountainous regions	Precipitation	Meteorological stations and satellite data
	Temperature (air, land)	Meteorological stations (air temperature), satellite (land surface temperature)
	Snow Cover	Multiple resolution satellite products available (daily-monthly; 250m-1km spatial resolution); GRACE satellite measurements (total water)
	Glacier characteristics (area, volume, change over time)	GRACE satellite measurements; remote sensing interpretation (size); in situ databases (Atlas of the Cyrosphere, Global Terrestrial Network for Glaciers)

4 Conclusions and policy applications

Scaling drives the progression of scientific analysis; it allows us to move from unpredictable observations, to pattern and process identification, to modeling systems (Levin 1992). Much progress has been made in the physical- and climate- science communities in reducing the uncertainty of modeling efforts, both because of advances in scientific understanding and greater collaboration across disciplines. Projects such as IMPACT2C, for example, which models potential impacts of a 2 degree Celsius warming, adopts a harmonized approach across disciplines to reduce uncertainty and enable inter-comparison of results (Jacob 2014).

Environmental systems differ in complexity, as does our scientific understanding of these systems. Thus, the scaling process provides a useful lens to guide vulnerability and adaptation studies. Case study results from this project recommend that environmental processes relevant to vulnerability and adaptation, such as rainfall recharge to freshwater lenses in small islands, or river discharge in coastal deltas and estuaries, warrant more attention for water sector concerns and policy development. Climate models are perhaps one of the only tools that can help us to understand what may happen to a given system. However, they operate on large spatial and temporal scales, they do not provide the needed historical perspective to understand vulnerability and adaptation, and they are not intended or designed for local level, current management. Frequently, however, climate models are misused for these purposes.

This project provided examples of alternative patterns, processes or phenomena to be measured, tools for measuring and monitoring, in the absence of, or in support of, modeling efforts. This information can be used by practitioners to inform local water resource and hazard management. A necessary part of doing so is to fully involve the modelers, to learn from their knowledge and wisdom, to incorporate their perspectives, and to ensure that modeling in the future will incorporate such experiences into the increasingly powerful models being run. This is a collaborative venture amongst us all, to ensure that models and modelers contribute to their fullest potential.

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Appendix Table 1: Excerpt table from data review for terrestrial resources.

Source	Description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	Environmental benefit	Appropriate Scale	Validation	Data access
National Aeronautics and Space Administration (NASA)	Aster Global Digital Elevation Model (GDEM)	30 m	global	one time	2009, 2011	medium	highest quality publicly available global DEM, useful for hazards modeling, general planning	local to global	http://www.jspacesystems.or.jp/ersdac/GDEM/ver2Validation/Summary_GDEM2_validation_report_final.pdf	http://asterweb.jpl.nasa.gov/gdem.asp
United States Geological Survey (USGS)	High resolution land cover derived from the Landsat satellite.	30 m	global	annual	2005; 2006	medium	high quality product, but out of date and would need to be locally validated and and made more specific utilizing local knowledge of land cover/land use	local to global	http://landval.gsfc.nasa.gov/sensor.php?SensorID=8	http://glcf.umd.edu/data/mosaic/
European Space Agency (ESA)	Moderate resolution land cover derived from the MERIS and ENVISAT satellites.	300 m	global	annual	2006; 2009	high	high quality product, but out of date and would need to be locally validated and and made more specific utilizing local knowledge of land cover/land use	national to global	http://due.esrin.esa.int/globcover/	http://due.esrin.esa.int/globcover/
Mangrove Forests of the World 2000	Classification of world's mangrove area derived from Landsat satellite data.	30 m	global	one time	published in 2010 using data from 2000	low	highest resolution global classification using consistent methodology, but using 2000 data	local to global	discussed in academic article (see Giri et al. 2010)	Giri, C., et al. "Status and distribution of mangrove forests of the world using earth observation satellite data." Global Ecology and Biogeography 20.1 (2011): 154-159.
Deforestation	Classification of global deforestation derived from Landsat satellite data.	30 m	global	one time	2000-2012	medium	high resolution, peer-reviewed global deforestation product	local to global	discussed in the academic article Hansen et al (2013)	Hansen, M. C., et al. "High-Resolution Global Maps of 21st-Century Forest Cover Change." science 342.6160 (2013): 850-853.

Source	Description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	Environmental benefit	Appropriate Scale	Validation	Data access
MODIS Land Cover Type	Yearly, moderate resolution land cover data derived from MODIS satellite data.	500 m	global	annual	December 1999-present	medium	useful as input for scientific models	national to global	http://landval.gsfc.nasa.gov/	available online through a variety of providers; http://modis-land.gsfc.nasa.gov/
MODIS Gross Primary Productivity	Yearly, moderate resolution gross vegetation productivity derived from MODIS satellite data.	1000 m	global	8-day	December 1999-present	high	useful as input for scientific models	national to global	http://landval.gsfc.nasa.gov/	available online through a variety of providers; http://modis-land.gsfc.nasa.gov/
MODIS Land Surface Temperature & Emissivity	Daily or 8-day land surface temperature derived from MODIS satellite data.	1000 m	global	daily or 8-day	December 1999-present	high	useful as input for scientific models	national to global	http://landval.gsfc.nasa.gov/	available online through a variety of providers; http://modis-land.gsfc.nasa.gov/
MODIS Fire & thermal anomalies	Daily or 8-day thermal anomalies derived from MODIS satellite data.	1000 m	global	daily or 8-day	December 1999-present	high	monitoring; management	national to global	http://landval.gsfc.nasa.gov/	available online through a variety of providers; http://modis-land.gsfc.nasa.gov/
Columbia University Center for International Earth Science Information Network (CIESIN)	Anthropogenic biomes of the world describes significant ecological patterns within the terrestrial biosphere casued by human interaction with ecosystems.	Raster cell sizes are 5 arc-minute or 0.08333 degree decimal (about 10 kilometers at the equator)	global	published in 2008	2008	medium	may have some benefit at national scale for larger geographic regions	national to global	refer to academic citation	http://sedac.ciesin.columbia.edu/data/set/anthromes-anthropogenic-biomes-world-v1

Source	Description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	Environmental benefit	Appropriate Scale	Validation	Data access
National Snow and Ice Data Center (NSIDC)	World Glacier Inventory provides glacier classification parameters from 1900-2003.	varies	global	varies	varies by dataset	low	glacier monitoring and classification	local to global	validation detailed in academic articles and website	http://nsidc.org/api/metadata?id=g01130
National Snow and Ice Data Center (NSIDC)	Global Land Ice Measurements from Space (GLIMS) will be a unique glacier inventory storing information about the extent and rates of change of the world's glaciers.	varies	global	varies	varies by dataset	low to high	glacier monitoring and classification	local to global	validation data will be provided when database launches	http://www.glims.org

Appendix Table 2: Excerpt table from data review for ocean resources.

Source	description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	environmental benefit	Appropriate Scale	validation	Data access
ReefBase; ReefGIS	A global coral reef database.	varies	global; including community monitoring data	Sea Surface Temperature (monthly mean); bleaching indices (12 week summary)	varies by product	high	excellent resource for raw and analysed products; background information/scientific information	local to global	Available in metadata and publications	(raw data) http://www.reefbase.org/gis_maps/datasets.aspx; online GIS (http://reefgis.reefbase.org/)
Sea Around Us Project	Information on the impact of fisheries on marine ecosystems globally.	varies	1950-present	varies with dataset	website reports that data is regularly updated	low	good place for general information on trends, but should be noted that dataset quality varies widely	national to global	error in reports can be high due to nature of sampling/reporting; dicussed in peer-reviewed publications	http://www.seaaroundus.org/data/
Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO); primarily altimetry data	Key products include Sea Surface Height, wind and wave data.	1/3 x 1/3 degree to 1/8 x 1/8 degree regional, 1 degree x 1 degree global	global for 1 x 1 degree; regional varies	varies with dataset	generally 1993-present	high	physical vulnerability assessments	national	accuracy reduces along coastline; see website for detailed comments/ publications	http://www.aviso.oceanobs.com/en/data/data-access-services.html
National Oceanic and Atmospheric Administration (NOAA)	Daily Sea Surface Temperature and Ice coverage.	1/4 deg. x 1/4 deg.	global	Daily	1984-present	high	scientific input for models	national	detailed in metadata	http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html
Hadley Sea Ice SST	Sea Surface Temperature from the Hadley Analysis Center.	1 deg. x 1 deg.	global	monthly	1870-present	high	scientific input for models	national	detailed in metadata	http://www.esrl.noaa.gov/psd/data/gridded/data.hadsst.html

Source	description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	environmental benefit	Appropriate Scale	validation	Data access
ICOADS products: Sea Surface and Air Temperature; Scalar Wind; Sea Level Pressure, others	Extensive collection of Ocean-Atmosphere datasets.	1 deg. x 1 deg.	global	monthly	1800-present; time period is defined in two segments, see metadata; irregular data updates*	high	common meteorological variables required for climate modeling in one format.	national to global	detailed in metadata	http://www.esrl.noaa.gov/psd/data/gridded/data.coads.1deg.html
MODIS Aqua Ocean Color	Ocean color which can be related to water quality.	4 km	global	daily	2002-present	high	scientific input for models	national to global	detailed in metadata	http://coastwatch.noaa.gov/
MODIS/Aqua and SeaWiFS Level 3 Daily Merged Chlorophyll Product	Chlorophyll-a concentrations globally.	9 km	global	daily	1997-2010	high	scientific input for models	national to global	detailed in metadata	http://coastwatch.noaa.gov/
AVISO (satellite altimetry products): Sea Surface Height, Wind and Waves, Indicators, In Situ Products	Key products such as mean sea-level rise indicator, Sea Surface Height, wind and wave datasets.	1/3 deg. x 1/3 deg.	global	model	1993-2013	high	scientific input for models	national to global	detailed in metadata	http://www.aviso.oceanobs.com/en/data/data-access-services.html
ReefBase	Coral bleaching indices.	4 km	global	monthly	2002-present	medium	scientific input for models; bleaching data for coastal managers	local to global	detailed in metadata	http://www.reefbase.org
World Resources Institute: Reefs at Risk Project	Coral reef location.	500 m	global	one time	collection date varies, publication in 2011	medium	scientific input for models	local to regional	detailed in metadata	http://www.wri.org/resources/data-sets/reefs-risk-revisited
General Bathymetry Chart of the Oceans (GEBCO)	Bathymetry	1 km	global	one time	2008	medium	input for enviornmental models/planning	national	detailed in metadata	http://www.gebco.net/data_and_products/gridded_bathymetry_data/
eSurge for ESA	Storm surge heights	varies	transect	varies	varies	medium	scientific input for models; near-real time data on storms	varies depending on data source	discussion on website	http://www.storm-surge.info/data-access

Source	description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	environmental benefit	Appropriate Scale	validation	Data access
US Geological Survey's Ocean Biogeographic Information Survey (OBIS) USA	Marine biological occurrence data.	varies	varies	varies	varies	high	scientific input for models; observational data for ecosystem services	varies depending on data source	accuracy and validation may vary widely	http://www.usgs.gov/obis-usa/data_search_and_access.html
International Union for the Conservation of Nature (IUCN)	Threatened species.	varies	varies	most recent is 2013	varies	medium	scientific data and reports for conservation planning	regional to global	discussion on website	http://www.iucnredlist.org/technical-documents/spatial-data

Appendix Table 3: Excerpt table from data review for population resources.

Source	Description	spatial resolution	spatial coverage	temporal resolution	temporal coverage	human resources	environmental benefit	Appropriate Scale	Validation	Data access
GeoHive	Tabulated population statistics: current, historical, estimates, projections, agglomerations, etc.	varies by dataset	national to global	varies by dataset	varies by dataset	medium	baseline for population	national to global	varies depending on resource being utilized, but in general, information is provided	http://www.geohive.com/
Socio-economic Data and Applications Center (SEDAC)	Global gridded population of the world.	population density estimate per area	local to global	varies by dataset	1990, 1995, 2000 and projected to 2015	medium	baseline for population	national	varies depending on dataset	http://sedac.ciesin.columbia.edu/data/collection/gpw-v3
SEDAC	Global Rural-Urban Mapping Project (GRUMP): population count, density, urban settlements/extent, political boundaries.	~ 1 km (30 arc seconds)	local to global	normalized for yearly representation	1990, 1995, 2000	medium	baseline for population in absence of more detailed data for migration/impact studies	national	varies depending on dataset	http://sedac.ciesin.columbia.edu/data/collection/grump-v1
SEDAC	Hazard and disaster risk maps for numerous hazard types.	varies by dataset	local to global	varies by dataset	varies by dataset	medium	planning and risk analysis	national to global	varies depending on resource being utilized, but in general, information is provided	http://sedac.ciesin.columbia.edu/theme/hazards
SEDAC	Road and transportation information.	other: vetor data	local to global	varies by dataset	varies by dataset	medium	planning and risk analysis	national to global	discussed in metadata/ online documentation	http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1
SEDAC	Global reservoir and dam information.	other: vetor and point data	local to global	varies by dataset	varies by dataset	medium	planning and risk analysis	national to global	discussed in metadata/ online documentation	http://sedac.ciesin.columbia.edu/data/set/grand-v1-reservoirs-rev01

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