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ENVSCI 1787 No. of Pages 17

ARTICLE IN PRESS

Environmental Science & Policy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Environmental Science & Policy

journal homepage: www.elsevier.com/locate/envsci

Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas

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ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form 6 May 2016
Accepted 9 May 2016
Available online xxx

Keywords:
Urban adaptation
Resilience
No-regret adaptation
Uncertainty
Adaptation gap

ABSTRACT

Urban areas are increasingly seen as having distinct need for climate adaptation. Further, as resources are limited, it is essential to prioritize adaptation actions. At the municipal scale, we suggest that priorities be placed where there is a gap between adaption need and existing adaptation effort. Taking Seattle, USA, as an example, we present this gap in terms of four categories of adaptation options (no-regret, primary, secondary, and tertiary) for the three primary urban hazards—flooding, heat wave, and drought. To do so, we first establish current adaptation need by identifying and categorizing adaptation options. Next, we consider for each option the number of hazards addressed and benefit to and beyond climate adaptation, the projected magnitude of the hazards addressed, the projection's uncertainty, and the required scale and irreversibility of investment. Third, we assessed Seattle's current adaptation efforts by reviewing adaptation plans and related materials. Finally, we identify the distance or "gap" as the proportion of adaptation options not identified by existing adaptation plans.

For Seattle, we categorized seven options as no-regret adaptation, five as primary, two as secondary, and three as tertiary. Each level's adaptation gap highlights significant opportunities to take steps to reduce climate risks in key areas.

1. Introduction

Four out of five of the top global risks in the next 10 years as identified by the World Economic Forum (2016) are related to climate change (World Economic Forum, 2016). Though these are global problems often discussed at the national scale, urban areas are increasingly seen as having a distinct role on the climate agenda, in terms of both mitigation and adaptation. The 21st session of the Conference of the Parties (COP 21), for example, highlighted the need to establish a global goal on adaptation to enhance adaptive capacity, to strengthen resilience and to reduce vulnerability to climate change. The Paris agreement references cities as relevant actors by acknowledging the need for non-Party stakeholders to address and respond to climate change (UNFCCC, 2015). Further, as of 2014, 81% of the US population (and more than 50% worldwide) resided in cities, making urban adaptation of particular importance. Vast urbanization is expected to continue and by 2050, the world will be one-third rural and two-thirds urban (United Nations, 2014).

1.1. Adaptation in cities

Along with their high concentration of people, there are several characteristics of urban areas that make them inherently vulnerable to climate risks and, therefore, important targets for adaptation. For example, the urban heat island makes cities more susceptible than surrounding rural areas to elevated temperature (Carter et al., 2015; Gartland, 2008; Smith et al., 2009). Urban impervious surfaces reduce infiltration and accelerate runoff so that cities are at heightened risk for flooding (Carter et al., 2015; Gill et al., 2007). And coastal city development often occurs in areas with high exposure to storms and sea level rise (Carter et al., 2015; Wilbanks et al., 2007).

In addition, there are unique benefits to focusing on urban level adaptation efforts as adaptation decisions are often made on the local level and require locality-specific actions (Adger, 2003). The

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http://dx.doi.org/10.1016/j.envsci.2016.05.007
1462-9011/

small scale of adaptation matches well with municipal government (Eriksen and Kelly, 2007).

To understand adaptation at the urban scale, it is important to recognize that climate change can manifest in both long-term stresses, such as water scarcity, and short-term shocks, such as extreme events with higher frequency, intensity and variability (IPCC, 2012; Venton and La Trobe, 2008). Therefore, urban adaptation includes a multitude of responses to climate change that range from generalized activities, such as reprioritized development, to highly specialized actions that address a particular climate impact, such as sea wall installation (McGray et al., 2007). As cities act on a variety of concerns, a means to prioritize adaptation strategies is helpful to efficiently address both short and long-term impacts. Prioritization at the government level helps leverage resources to address relevant climate risks (either through direct engagement or indirectly through funding or collaborating with private or non-profit sector), and promotes investments in activities with great efficiency and ancillary benefits.

1.2. Adaptation options and categories

We identify four categories of adaptation options: no-regret, primary, secondary, and tertiary adaptation. To place adaptation options in these categories, we consider the number of hazards each option addresses and its benefit to and beyond climate adaptation, the projected magnitude of the hazards addressed, the uncertainty of future hazard projections, and the required scale and irreversibility of investment.

In our framework, options that address multiple climate hazards and non-climate related common city issues are considered *no-regret adaptation options*. As the non-climate issues constitute city priorities that will persist regardless of climate change, these options can typically be justified under various climate scenarios (Hallegatte, 2009; Willows and Connell, 2003; World Bank, 2013) and at various levels of investment. Because of this broad coverage, cities could consider the no-regret options as a top priority when allocating budgets.

Next, *primary adaptation options* are designed to address a specific future climate hazard where there is a projected increase in hazard magnitude compared to the historical baseline and where there is low degree of uncertainty around these projections. There are many sources of uncertainty related to climate change, including, but not limited to, the social and economic development pathways and hence carbon emission scenarios, the uncertainty of nature climate variability, or the uncertainty of catastrophic events like the shutdown of North Atlantic Circulations. In addition, climate models vary in their capacities to project the future in a reliable manner. The degree to which climate models agree with one another in terms of the future projection is therefore valuable in understanding uncertainties embedded in climate modeling. Options addressing a hazard with a projected increase in magnitude where climate models show a high degree of agreement are therefore considered *primary adaptation*, in our framework, as investment to address this type of hazard allows for lower likelihood of resource wasting.

If there is not both an increase in projected magnitude and high agreement among climate models, we argue that an option's amount of investment should be considered. This leads to the *secondary* and *tertiary adaptation* categories. If the option does not entail large-scale or irreversible investment, risk-averse decision makers may still wish to take action to cope with future risks. These are categorized as *secondary adaptation*. Finally, there are the *tertiary adaptation options* where an option does entail large-scale investment and irreversible outcomes. As irreversible adaptation investments are usually long-lived, these options entail high fixed cost, sunk cost and adjustment costs (Reilly and Schimmelpfennig, 2000). Therefore, irreversibility and investment cost usually are considered concurrently and in our framework irreversibility only applies to large-scale adaptation investment with high cost.

While we argue that no-regret options should be the top priorities for cities, primary, secondary, and tertiary options are more open to interpretation; a city can evaluate its own situation and prioritize accordingly. Here we provide a starting point for exploring adaptation options and an order for their pursuit.

1.3. Adaptation gap

Another way to prioritize adaptation actions is by identifying an "adaptation gap." There are many ways to define and quantify the "gap," such as the difference between existing adaptation efforts, and adaptation potential (Climate Analytics, 2015) or a societal set goal for adaptation (UNEP, 2014). We define "adaptation gap" as *the difference between existing adaptation efforts and adaptation need*. Gap analysis is helpful for multiple reasons. First, it is easily integrated in current procedures and operational structures when it comes to the climate policy planning and evaluation (UNEP, 2014). In addition, gap analysis is flexible and can be easily modified to fit the specific needs and risks of a particular city; a city may choose to re-rank or exclude individual options given their city's context and their local knowledge. For example, the categorization of "no-regret" adaptation options prioritizes a consideration of an option's value over its cost, which a city may elect to change.

Second, gap analysis points to actionable outputs. Linking information to decisions and then to actions is a significant challenge to overcome in the implementation of climate change adaptation (Mastrandrea et al., 2010). The gap analysis approach relies on vulnerability assessment through indicators that imply key adaptation actions. The resulting "gap" measured against these actions points to priorities for a city to consider. Finally, gap analysis also allows for tracking over time. Persistent gaps exist between knowledge of adaptation challenges, resilience policy and actual implementation (Lemos et al., 2012). The progress of adaptation therefore needs to be continuously reviewed, and repeated gap analysis provides one method of such review (Davoudi et al., 2011). If needed, the framework provided by this study can be repeated in future years to track the progress made in reducing the adaptation gap.

An adaptation gap analysis approach is not without its challenges. It is difficult to apply uniformly across cities due to diverse climate risks and varied city context (UNEP, 2014), and there is no level of perfect adaptation to measure against. There has been progress made in measuring one kind of adaptation gap equivalent to the distance between financial need and financial provisions (UNEP, 2015), but a general gap assessment framework for adaptation actions is still lacking. This project, therefore, helps to further protocols for adaptation gap analyses and creates a useable framework despite these challenges.

This paper measures the adaptation gap for an example city by comparing adaptation options with the city's adaptation planning materials. "Gaps" represent the proportion of the identified options that are not yet covered by the plans. This gap measurement therefore provides an assessment of the city's preparedness for future climate hazards as well as suggesting opportunities for improvement. The analysis focuses on the primary urban hazards (flooding, heat wave, and drought) (Hunt et al., 2011) but could be expanded to other hazards. The methodology presented here could be augmented to include other types of climate-related hazards, such as wind hazard, extreme winter weather or exacerbated air or water pollution, given available data. The hazards we consider follow readily from global

Please cite this article in press as: C. Chen, et al., Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas, Environ. Sci. Policy (2016), http://dx.doi.org/10.1016/j.envsci.2016.05.007

and regional climate projections. Other risks such as localized extreme weather events are much more uncertain to be accurately projected than the risks considered here (Knutti and Sedláček, 2012). Such efforts to assess adaptation need in comparison to a city's current situation is critical to advancing our understanding of adaptation generally and accelerating its application globally.

2. Methods

In evaluating adaptation priorities for Seattle, Washington USA, this paper provides a method of adaptation assessment composed of three steps: (1) establish current adaptation need by identifying and categorizing adaptation options; (2) survey current adaptation efforts by gathering and reviewing relevant adaptation plan materials; and (3) identify the adaptation gap based on the outputs from the first two steps.

2.1. Step I: identify and categorize adaptation options

To establish current adaptation need, we first identified a list of hazard-specific adaptation options for flooding, drought, and heat wave. We then developed and applied a process to prioritize adaptation options that address those hazards.

2.1.1. Develop list of adaptation options

To identify possible adaptation options, we consulted 39 experts (Appendix A) to compile indicators that capture a city's ability to respond to future climate hazards. Experts were chosen to represent diversity across subject area (urban environment, climate change, resiliency theory, disaster risk management, etc.) and sector (academic, non-profit, government, and private). We shared 120 preliminary indicators for experts to critique through a survey. Based on expert feedback, about 80% of these indicators were excluded. 40 new indicators were added based on survey responses and subsequent expert engagements (an in-person meeting, 29 bilateral phone meetings and 4 small group regional meetings). A new set of indicators was therefore created for final feedback by a subset of 9 experts. This iterative process lasted 10 months and yielded 33 indicators (Appendix B) as proxies to measure vulnerability and readiness to cope with climate hazards. Table 1 below explains the options derived from each indicator; each indicator suggests a particular adaptation objective and corresponding adaptation option(s). For example, suggested indicators related to the hazard of heat waves include coping capacities that can be affected by policy, such as the percentage of the population with poor or fair health or amount of population that cannot afford medical services.

2.1.2. Categorize adaptation options

To categorize the options listed above in Table 1, we consider the number of hazards each option addresses and its benefit to and beyond climate adaptation, the projected magnitude of the hazards addressed, the uncertainty of future hazard projections, and the required scale and irreversibility of investment. These steps are outlined in in Fig. 1 below and subsequently explained in further detail.

First, we reviewed options from Table 1 and, relying on expert feedback and relevant literature when needed, we assessed which options had potential to benefit cities in general by addressing multiple climate hazards and non-climate, common city issues and categorized them as *no-regret adaptation* (versus those options that address only one climate hazard).

Following the steps in Fig. 1, we next focused on the options addressing a specific hazard. We determined the projected magnitude of the hazard compared to the historical baseline for our example city, Seattle. To do so, we evaluated the magnitude projections under two climate scenarios, RCP 4.5 and RCP 8.5 (Van Vuuren et al., 2011). Each hazard is assessed by a climate extreme index (Sillmann et al., 2013) at Seattle's geographic centroid (see Appendix C). Flooding hazard is measured by *monthly maximum consecutive 5-day precipitation* (rx5 day). Drought hazard is measured by *maximum length of dry spell* (cdd), or the maximum number of consecutive days with daily precipitation less than 1 mm. And heat wave hazard is measured by *warm spell duration index* (wsdi), or a count of days with at least 6 consecutive days when daily maximum temperature is higher than the 90 percentile of the maximum temperature in the base period (1961–1990). These indices have been cited for climate monitoring by World Meteorological Organization and are relatively easy to compute using climate projection data. However, we acknowledge that they are not the only way to measure the intensity of climate hazard.

We calculated a historical baseline and two future profiles for each hazard under two scenarios, both of which were for the years 2020–2049. We selected this time frame because it lies within the time horizon of many city-planning activities while also allowing for significant climate effects to materialize. Further, within 30–50 years, cities are able to make and implement plans that affect their resilience and adaptive capacities to confront changing climate conditions.

To calculate the historical baseline for each climate index, 1950–1999 temperature and precipitation observations were first obtained from the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive[1] (Climate Analytics Group, 2014; Maurer et al., 2010, 2002; Reclamation, 2013). We then compute climate indices using temperature and precipitation projections. The values of climate indices quantify the magnitude of each climate hazard. We then averaged index values over the 50 years to estimate the baseline of hazard magnitude.

For future projections, we used the projection results under two climate scenarios, RCP 4.5 and RCP 8.5, 2020–2049, again from the Downscaled CMIP3 and CMIP5Climate and Hydrology Projections archive (Maurer et al., 2010; Reclamation, 2013). Future temperature (daily maximum-temperature, minimum-temperature) and precipitation (BCCA bias-corrected precipitation) projections are obtained from a multi-model ensemble comprising one run per scenario from each of the models in (Appendix C). The projections are statistically downscaled to a 0.125° spatial scale. With these data, we computed the annual hazard magnitude for each model from 2020 to 2049. The expected hazard magnitude is quantified by the ensemble mean over 30 years (2020–2049), for both climate scenarios. Therefore, our expected hazard magnitude describes the future 30-year average climate hazard due to the change of temperature and precipitation, under RCP 4.5 and RCP 8.5.

To account for uncertainty, we then assessed degree of agreement among climate models. The 19 individual model outputs are shown below in Fig. 2. To analyze uncertainty from climate models, we calculated coefficient of variation for each hazard in terms of the expected magnitude for each model. We considered a relatively high degree of agreement if the coefficient of variation is less than 50%.

Options addressing a specific hazard with a projected increase in magnitude and high degree of agreement among climate models may be valuable investments and were categorized as *primary adaptation*. If an option not does meet these two criteria, investment may be less justified and therefore requires further consideration. In general, infrastructure construction and retrofitting are considered large-scale investment that result in irreversible outcomes (Hallegatte, 2009). In addition, population

[1] Data archive is located at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

Table 1
Adaptation options for flooding, heat wave, and drought hazards (Bradford et al., 2015; CDC, 2012, 2015; Contestabile, 2013; EPA, 2002, 2011; FEMA, 2009, 2014; Gentry et al., 2014; NRDC, 2014; USGS, 2013; United Nations, 2015).
(Italic text provides explanation for each option, per expert opinion).

Hazard	Adaptation objective	Adaptation options
Flooding	Enhance capacity of monitoring and assessment	Monitoring flood risks and updating flood risk assessment on a regular basis *Many international disaster management frameworks (e.g. Hyogo, Sendai) consider regular updates of risk assessments that reflect changing future risk scenario important, since risk assessment is considered a crucial part of risk management strategies (United Nations, 2015). Similarly, to manage future impacts of climate change and plan for adaptation actions, planning should reflect updated knowledge on climate impacts and risk profiles*.
		Enhancing city-wide early warning systems *An efficient early warning system can effectively prepare cities for flooding*
	Reduce the sensitivity of built environment	Regulating the installation of vulnerable housing types like mobile or manufactured homes *Affordable housing, such as manufactured or mobile homes, have historically been vulnerable to multiple weather shocks, including flooding. Through better installation regulation, cities can improve the flooding resistance of this type of housing (FEMA, 2009)*
		Increasing green space or/and improving green storm water infrastructures *Impervious surface lessens the amount of storm water runoff that infiltrate into the ground during excessive rainfall. Increasing green space or improving the green storm water infrastructure could offset this disadvantage.*
		Separating sewer system from storm water (and other surface runoff) drains *When the system exceeds its capacity due to excessive storm water, combined sewer systems may cause discharge of untreated wastewater directly to the surface. As a costly infrastructure retrofitting option, making a separate storm water draining system is the solution to eliminate the chance of sewer overflows during heavy rainfall (EPA, 2011)*
	Reduce sensitivity of population health	Improving the overall health of the population; reduce the proportion of the population with poor or fair health, especially the elderly *Epidemic is one of the post-flooding risks for communities, due to factors like contaminated drinking water, damp environments, or disruption of public health services. In addition, flooding can cause infection through bodily exposure as well as non-infectious outcomes like injuries. The portion of the population in poor or fair health, especially the elderly, is particularly vulnerable. Improving overall health conditions helps to reduce the vulnerability to post-flooding health threats (CDC, 2012).*
		Increasing the affordability of health care services *When post-flooding diseases threaten lives and livelihoods, the low-income population that lacks health insurance will be largely affected. Providing or improving affordable health care helps address the vulnerability of this particular group, hence the overall vulnerability of a city.*
	Reduce sensitivity of population living in flood-prone areas	Relocating residents in floodplains to safer places *Relocating the entire community is considered the only viable way to adapt to flooding in extreme cases (Contestabile, 2013). Though costly, moving those that are living in vulnerable conditions may be needed in high-risk scenarios.*
	Enhance capacities of local transport	Making public transport easier to access (closer to housing), and more frequent during flood events *FEMA considers evacuating the area the safest way to survive a*

	infrastructure in the event of evacuation	*flood (FEMA, 2014). Public transportation is particularly important for those that do not own private vehicles or do not have access to private transport. Improving the accessibility of public transport reduces the vulnerability of the disadvantaged group.*
	Enhance capacities to control water quality amid flooding	Guaranteeing the quality of drinking water *The general capacity of providing clean drinking water reflects overall capacity to effectively deal with emergencies that threaten drinking water quality amid disruptive events, including flooding.*
		Improving the capacity of wastewater treatment by increasing the volumes of water treated, moved, and reused through the treatment system. *Expanding the wastewater treatment capacity is a way to control the incidence of combined sewer overflows and the contamination of surface water due to overflow.*
Heat Wave	Enhance capacity of monitoring and assessment	Updating heat risk assessment on a regular basis, based on vulnerability assessment and future hazard projections *Risk assessment is important for preparing to address heat hazard*
		Enhancing early warning systems, especially for vulnerable groups (e.g. the elderly population, those with poor health, or low-income.) *An efficient early warning system can effectively prepare cities for heat waves, especially vulnerable groups*
	Reduce sensitivity of population health	Improving accessibility of affordable electric resources for home cooling *Providing electric energy to the low-income population helps to increase the use of home cooling and reduce the impact of heat wave to human health.*
		Expanding green spaces, including tree canopy coverage, green roof, or other forms of urban forestry *Green spaces provide passive cooling to mitigate the impact of heat waves (Gentry et al., 2014)*
		Improving accessibility of public buildings that are equipped with cooling facilities *For people that do not have access to home cooling, an alternative is to enter public buildings, for instance, shopping malls, to cope with a heat wave. When extreme heat occurs and emergency plans are launched, accessibility of such cooling centers protects residents who would otherwise suffer (Bradford et al., 2015)*
		Improving the overall health of population, that is, reducing the proportion of the population with poor or fair health, especially the elderly *The portion of the population that suffers from chronic diseases is particularly vulnerable when a heat wave strikes. Improving health conditions makes the overall population less vulnerable (CDC, 2012, 2015)*
		Increasing the affordability of health care services *Heat waves may exacerbate chronic health conditions of the*

relocation is considered to have a high degree of irreversibility (Ranger and Garbett-Shiels, 2011). We categorized the four adaptation actions for Seattle according to these guidelines (options that do not entail large-scale, irreversible investment were categorized as *secondary adaptation* and options that do were categorized as *tertiary adaptation*). However, such a classification may differ among cities based on local context.

After following the process in Fig. 1, all options in Table 1 were categorized in one of four categories. *No-regret options* address climate and non-climate related issues faced by cities without considering uncertainty of climate change and its impacts. Those options have potential to reduce vulnerability in general and empower cities to cope with multiple future climate hazards. These options may provide capacities to cope with their non-climate hazards as well, such as seismic risk that is considered a particular non-climate hazard for Seattle. Investments are therefore justified no matter how climate change materializes in the future. *Primary options* address a specific future climate hazard for which climate models show high agreement and a projected increase in magnitude compared to the historical baseline. Additional investments are therefore justified. *Secondary options* address a specific future climate hazard without both a projected increase in magnitude and high agreement among climate models, but do not entail large-scale investment or irreversible outcomes. *Secondary* options are for decision-makers who seek to make relatively minor investments to increase their safety margin. Finally, *tertiary* options also address a hazard without both a projected increase in magnitude and high agreement among climate models, but do but entail large-scale, irreversible investment.

		vulnerable population. Accessibility of affordable general health care services helps to reduce vulnerability when heat wave impacts occur.
		Increasing the accessibility of emergency medical facilities (emergency rooms, acute hospital beds, etc.) especially for the low-income population *While the low-income population, who may be lacking access to home cooling facilities, is particularly vulnerable to a heat wave, they are also less able to afford emergency health care. Making emergency medical facilities more accessible reduces the vulnerability of this group, hence the overall vulnerability of the city.*
Drought	Enhance capacity of monitoring and assessment	Updating drought risk assessment on a regular basis, based on water scarcity assessment and future hazard projections *Risk assessment is important for preparing to address drought hazard*
		Enhancing early warning systems for households and water-intensive industries *An efficient early warning system can effectively prepare cities for drought by improving awareness and taking timely actions.*
	Reduce sensitivity of water supply	Increasing public awareness on water scarcity *Limiting water waste is important when water supply drops dramatically due to drought. Increasing public awareness of water scarcity is one way to limit water waste.*
		Reducing water stress through implementation of conservation programs *Conservation programs help to alleviate water stress when drought strikes water-intensive industries and households (EPA, 2002)*
		Using a policy instrument, for instance, water pricing, to regulate water usage and control wasting, especially at the industry level *In extreme cases, pricing is an effective way to prevent wasteful water use and to promote urban water efficiency (NRDC, 2014)*
	Enhance capacities to deliver quality drinking water amid drought	Guaranteeing the quality of drinking water *Drought potentially jeopardizes water quality since water contaminants are concentrated when water levels decrease. Sustaining high quality of drinking water by controlling contamination in the water sources is an effective way to continue delivering safe drinking water when drought strikes (USGS, 2013).*

2.2. Step II: survey current adaptation efforts

We analyzed nine adaptation-planning documents produced by a variety of Seattle's municipal government agencies, including utilities and citywide planning committees (Table 2). These documents are the official planning documents we were aware of at the time of analysis. In each document, we identified either forthcoming or already implemented discrete actions, initiatives, ideas, and policies that relate to the adaptation options identified and categorized in Step 1. For example, one adaptation option identified in Step 1 is improving accessibility of public buildings that are equipped with cooling facilities. We related to this option to every action from Seattle's adaptation planning materials that included mention of cooling centers serving vulnerable populations, among others.

Some adaptation options are not included in the adaptation plan materials of Table 2. For example, some options are not addressed in adaptation planning because the City is already high preforming in these areas or they are addressed in non-climate related city planning documents or initiatives. To identify options being pursued outside of adaptation plans, we conducted additional research and consulted with two city personnel. A gap exists if an option is not planned anywhere and the city has not shown evidence of high performance.

2.3. Step III: calculate the adaptation gap

We next identified the gap between adaption options (Step 1) and existing adaptation efforts (Step 2). Specifically, the gap is the proportion of adaptation options that we did not find in Seattle's planning documents. We calculated the gap for each adaptation category: no-regret, primary, secondary, and tertiary across all three climate hazards.

3. Results

3.1. Step I: identify and categorize adaptation options for Seattle

Options addressing multiple climate hazards and common city issues beyond climate change were categorized as no-regret adaptation (see Table 5 below). For options addressing a specific hazard, the projected hazard magnitude and degree of agreement among climate models was evaluated.

Comparison of historical and projected magnitude for each hazard is shown in Table 3 below. Seattle experienced flooding 18 times over the past 20 years (SHELDUS, 2015) and is currently considered prone to flooding (Seattle Office of Emergency Management, 2014). Its historical average magnitude is 95 mm 5-day monthly maximum rainfall, which is projected to decrease under both future climate scenarios (94 mm under RCP 4.5 and

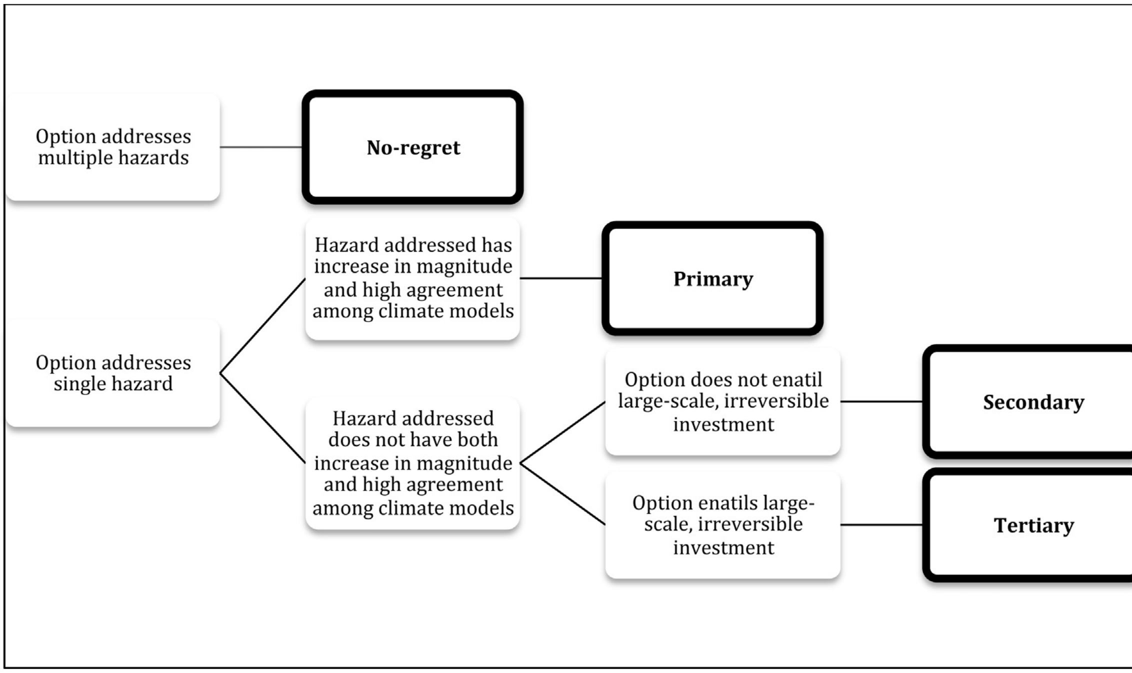

Fig. 1. Steps to categorize adaptation options.
Outlined boxes are the four categories of adaptation options.

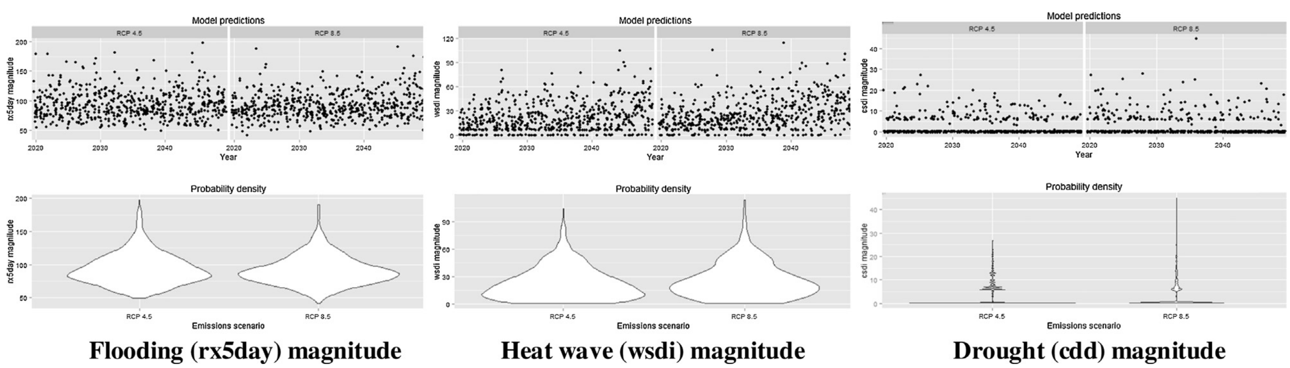

Fig. 2. Magnitude projection of future hazards, based on projections of 19 climate models (from left to right: flooding hazard; heat wave hazard; drought hazard) The jittered dotplots show each model's prediction for each year, under each of two RCP scenarios, for each of the three climate indices used in this paper. The associated violin plots show the estimated probability density for each climate-index magnitude.

91 mm under RCP 8.5). For heat wave hazard, there were two recorded heat wave events for Seattle over the past 20 years (Table 3). The historical average magnitude is 43 days of warm spell duration, which is projected to increase under both future climate scenarios (32 days under RCP 4.5 and 38 days under RCP 8.5). For drought hazard, there was only one recorded drought event for the past 20 years (Table 3). Its historical average magnitude is 100 days of dry spell duration, which is projected to increase under both future climate scenarios (109 days under both RCP 4.5 and RCP 8.5).

In terms of the degree of agreement among climate models, Table 4 below shows that climate models used for each hazard in this analysis have a high degree of agreement on the expected

Table 2
Seattle's adaptation planning documents.

Name of Plan	Agency/Office	Year
Comprehensive Emergency Management Plan	Seattle Office of Emergency Management	2015
Disaster Recovery Framework	Seattle Office of Emergency Management	2015
Integrated Resource Plan (IRP)	Seattle City Light	2014
SHIVA—The Seattle Hazard Identification& Vulnerability Analysis	Seattle Office of Emergency Management	2014
Seattle's Climate Action Plan	Seattle Office of Sustainability and Environment	2013
Toward a Resilient Seattle: Post-Disaster Recovery Plan Framework	City of Seattle	2013
Water System Plan	Seattle Public Utilities	2013
Seattle Disaster Readiness and Response Plan	Seattle Office of Emergency Management	2012
Seattle All-Hazards Mitigation Plan	Seattle Office of Emergency Management	2009

Table 3
Historical and projected hazard profile for Seattle.

	Historical Event(s) *(Data from SHELDUS, 2015)*, 1995–2014	Historical Average Magnitude	Projected Expected Magnitude (2020–2049)	
			RCP 4.5	*RCP 8.5*
Flooding (rx5 day)	18 recorded floods	95[2]	94[2]	91[2]
Heat wave (wsdi)	2 recorded heat wave	4[3]	32[3]	38[3]
Drought (cdd)	1 recorded drought event	100[4]	109[4]	109[4]

Table 4
Climate model coefficients of variations.

	Degree of Agreement Among Models (Coefficient of variations) on the Expected Future Magnitude of the Hazard	
	RCP 4.5	*RCP 8.5*
Flooding (rx5 day)	5.9%	7.93%
Heat wave (wsdi)	34.63%	33.9%
Drought (cdd)	12.44%	13.27%

magnitude of each hazard (as shown by all coefficients of variations being smaller than 50%).

Since all hazards show high degree of agreement among climate models, only those options that specifically address a hazard with a projected increase in magnitude (drought and heat wave) are considered *primary* adaptation options, as summarized in Table 5 below. Options specifically addressing a hazard without a projected increase in magnitude (flooding) are either *secondary* or *tertiary* adaptation, depending on the level of investment and irreversibility.

Of the options that address a flooding hazard, we identified which have potential to entail large, irreversible investment (i.e. *tertiary*). Irreversibility and investment scales are estimated based on Hallegatte (2009) and Ranger and Garbett-Shiels (2011). The remaining options for flooding do not entail large-scale investment and irreversible outcomes and are thereby categorized as *secondary* (summarized in Table 5 below).

3.2. Step II: survey current adaptation efforts in Seattle

While all plans listed in Table 2 were reviewed, Seattle's *Climate Action Plan* became the primary document for this analysis because it includes information on all the hazards considered here, planning information, and descriptions of both intent and timeline for implementation. Therefore, we first checked the *Climate Action Plan* when reviewing for the adaptation options and in the event an option was not found, then turned to the additional plans listed in Table 2. Details of this process are show in in Table D1 in Appendix D.

3.3. Step III: calculate the adaptation gaps for Seattle

A majority of the adaptation options identified are being considered by Seattle in its adaptation planning and implementation. The adaptation plan materials cover five of the seven adaptation options that are *no-regret* (gap = 29%). There are gaps in making health care services more affordable, and enhancing early warning systems. The early warning system Seattle has, although comprehensive lacks efficiency and includes a barrier to access. An initiative to improve the system is lacking in adaptation plan materials. The adaptation plan materials cover all five of the primary adaptation options (gap = 0%). The adaptation plan materials cover the two adaptation options identified as secondary (gap = 0%). Seattle's adaptation plan materials cover one out of the three adaptation options identified as tertiary (gap = 67%). There is a gap in retrofitting the combined sewer system to separate it from storm water drainage to eliminate the chance of combined sewer outflows. In addition, there is a gap in improving the capacity of wastewater treatment.

4. Discussion

As cities act on a variety of concerns related to climate impacts, a means to prioritize strategies is important to efficiently utilize limited city budgets. An adaptation gap framework can be helpful in this effort because adaptation priorities can be identified where gaps exist. While there are many possible approaches to identify an adaptation gap, this paper provides a framework based on identified adaptation needs and current adaptation efforts.

For the three climate hazards, flooding, drought, and heat waves, we found a relatively small gap between Seattle's climate risks and adaptation opportunities in its existing adaptation actions and plans. Gap scores show that the City's adaptation plan materials have aimed to address a majority of the adaptation options. Nevertheless, Seattle's no-regret adaptation gap highlights significant opportunity for adaptation and prepares decision-makers to take steps to reduce risks in key areas.

In our definition, investments for options that reduce city's vulnerability to multiple climate hazards and help to deal with common city issues even in the absence of climate change are no-regret strategies. The no-regret options identified in this paper (Table 5) help to reduce factors contributing to the "contextual vulnerability" (O'Brien et al., 2007) of the city and its residents. Since contextual vulnerability describes social characteristics as a result of multiple factors and processes not necessarily related to climate change, actions that improve these factors potentially generate benefits not limited to climate adaptation. For instance, expanding green space would potentially be helpful for stormwater management and flood control, as well as building a cooler and more drought-resistant city. Meanwhile, investing in green space also addresses other priorities in city's agenda, such greenhouse gas mitigation, pollution reduction, and biodiversity protection. Financing a no-regret option does not need to compete with other non-climate priorities to which a city has to allocate its

[2] unit: mm rainfall in 5-day interval.
[3] unit: days of warm spell duration.
[4] unit: days of dry period duration.

Table 5
Seattle's No-Regret, Primary, Secondary, and Tertiary Adaptation Options. The " + " sign stands for reversible or small-scale options. The "−" sign stands for options otherwise. "N/A" refers to criteria not addressed by the category of adaptation.

Category of Adaptation Options	Adaptation Option	Benefit	Reversibility	Small-scale investment
No-Regret Adaptation	Updating major risk assessment on a regular basis	To address multiple climate hazards (heat wave, drought, flooding) but also for general, non-climate risk management	N/A	N/A
	Enhancing early warning systems to communicate about upcoming hazardous events	To address multiple climate hazards (teat wave, drought, flooding) but also for general, non-climate risk management	N/A	N/A
	Improving the overall health of population, especially the vulnerable population	To addressing heat wave and flooding hazards, but also is a general action even if climate change is not considered.	N/A	N/A
	Increasing the affordability of health care services	To address heat wave and flooding, but also is a general action even if climate change is not considered.	N/A	N/A
	Increasing the accessibility of emergency medical facilities (emergency room, acute hospital bed etc.) especially for the low-income population	To address heat wave and flooding, but also is a general action even if climate change is not considered.	N/A	N/A
	Expanding green spaces, including tree canopy coverage, green roof, and green storm water infrastructures	To address heat wave and flooding, but also is a general action even if climate change is not considered.	N/A	N/A
	Guaranteeing quality of drinking water	To address drought and flooding, but also is a general action even if climate change is not considered.	N/A	N/A

limited budget. Throughout the continuum of actions as responses to climate change (McGray et al., 2007), no-regret adaptation actions are the ones that can be mainstreamed into city's development planning through its day-to-day operations.

Although each primary adaptation option helps to address one type of hazard, if climate models show a relatively high degree of agreement and an increased hazard magnitude, investment in these options can be justified. Therefore, after considering no-regret options, primary options represent additional steps for a city to take to reduce risk. Consideration of the remaining options, secondary and tertiary, will be largely contextual; they will depend on the city's budget, available resources, and risk preferences, and so forth.

It is important to point out that though our framework can be applied to any city, identified adaptation options and how they are grouped into the four priority categories will differ amongst cities.

Primary Adaptation	Improving accessibility of affordable electric resources for home cooling	Address heat wave	N/A	N/A
	Improving accessibility of public buildings that are equipped with cooling facilities	Address heat wave	N/A	N/A
	Increasing public awareness on water scarcity	Address drought	N/A	N/A
	Reducing water stress through implementation of conservation programs	Address drought	N/A	N/A
	Using policy instrument, for instance, water pricing, to regulate water usage and control wasting at industry level	Address drought	N/A	N/A
Secondary Adaptation	Regulating the installation of vulnerable housing types like mobile or manufactured homes	Address flooding	+	+
	Making public transport easier to access (closer to	Address flooding	+	-
	housing), and more frequent during flood events			
Tertiary Adaptation	Retrofitting sewer system to separate from storm water (and other surface runoff) drains	Address flooding	-	-
	Relocating residents in floodplains to safer places	Address flooding	-	-
	Improving the capacity of wastewater treatment by increasing the volumes of water treated, moved, and reused through the treatment system	Address flooding	-	-

Applied elsewhere, our gap analysis may prioritize different options because the city faces unique climate risks given its geography or because of the difficulty of implementing various options in different contexts. Therefore, we have included a general assessment of all options' level of investment and irreversibility in Appendix E.

Our paper is among the first attempts to quantify an adaptation gap. The definition of adaptation gap could vary depending on the purpose of measurement (UNEP, 2014), and the methodology of a global adaptation gap will continue to mature over time. Our framework to identify adaptation priorities serves to supplement global adaptation goals (if any) with a city level analysis reflecting common practice and emphasizing hazard-specific responses.

Our study relies heavily on expert opinion about what actions constitute adaptation and how those actions address climate hazards. Many factors will shape the recommendation for adaptation actions. For example, experts and decision-makers will vary in their evaluation of co-benefits (e.g., importance of gender or socioeconomic justice). It is also likely that common practice in adaptation planning will evolve and change, given improved climate information and growing public understanding of climate change risk. Still, a gap analysis approach can be useful, even though priorities and information vary over time and space.

The ultimate aim of adaptation planning is risk reduction to human and natural systems. Time will tell if the priorities and implemented actions are effective in achieving that goal. Regardless, limited funds will necessitate priority-setting and a systematic approach to that priority-setting promotes transparency and allows for monitoring of progress. With COP21's acknowledgement of the importance of adaptation in urban areas, researchers and practitioners must move to grow our understanding of adaptation actions and outcomes.

Acknowledgements

This work was pursued under the auspices of ND-GAIN's Urban Adaptation Assessment, a project funded by the Kresge Foundation. Authors are grateful to Susi Moser for advising, and to Paul

Fleming and Tracy Morgenstern for their insights on adaptation practices in Seattle.

We also acknowledge the World Climate Research Programme's Working Group on Coupled Modelling (see Appendix C). For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Appendix A.

Urban Adaptation Assessment Advisors.

The Urban Adaptation Assessment includes an advisory committee of leading U.S. adaptation influencers, including both researchers and practitioners working on climate resilience. Advisors are listed below and organized by their academic, public, private or non-profit affiliations.

Academic

Vicki Arroyo, J.D.
Executive Director, Georgetown Climate Center, Georgetown University

Dr. Melissa Kenney
Research Assistant Professor, Environmental Decision Science and Indicators, University of Maryland

Dr. Kelly Klima
Research Scientist, Carnegie Mellon University

Dr. Rob Melnick
Executive Director, Julie Ann Wrigley Global Institute of Sustainability
Presidential Professor of Practice, School of Sustainability, Arizona State University

Dr. Anand Patwardhan
Professor, School of Public Policy at the University of Maryland, College Park/Shailesh Mehta Chair
Professor, School of Management, Indian Institute of Technology-Bombay

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Ron Simms
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John Zeanah
Administrator, Memphis-Shelby County Office of Sustainability

Private

Dr. Shannon Bouton
Chief Operating Officer, McKinsey Center for Business and Environment

Ira Feldman
President and Senior Counsel, Greentrack Strategies

Gary Lawrence
Former Vice President and Chief Sustainability Officer, AECOM Technology Corporation

Braulio Eduardo Morera
Associate, International Development, Arup

Dr. Susanne Moser
Director and Principal Researcher, Susanne Moser Research and Consulting

Dr. Raj Rajan
Vice President, RD&E, Global Sustainability Technical Leader, Ecolab

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Former Senior Vice President, Head Sustainability Americas Hub, Swiss Re

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Helen Ng
Executive Vice President, World Council on City Data Director, Global City Indicators Facility

Sascha Petersen
Climate Change Adaptation Specialist, Adaptation International,
Former Managing Director, American Society of Adaptation Professionals, Institute for Sustainable Communities

Robert Puentes
President and CEO, Eno Center for Transportation
Non-Resident Senior Fellow, Brookings Institution Metropolitan Policy Program

Andrew Salkin
COO, 100 Resilient Cities Pioneered by the Rockefeller Foundation

Katie Vines
Former Head of Adaptation Research, C40Cities

Katie Walsh

Cities Manager for North America, CDP
Kristi Wamstad-Evans
Technical Director, STAR Communities
Karen Weigert
Senior Fellow for Global Cities, Chicago Council on Global Affairs
Former Chief Sustainability Officer, City of Chicago
Alisa Zomer
Urban Researcher and Manager, Environmental Performance Index, Yale University

Appendix B.

Selected Urban Adaptation Assessment Indicators.

The Urban Adaptation Assessment looked at various aspects of a city's features that affect its vulnerability to the impacts of climate hazards and its general capacity to take on adaptation actions. A list of indicators was selected to measure vulnerability and capacity, through an iterative process instructed by experts' opinions. These indicators reflect those factors that would alter the negative impacts of natural hazard on lives and livelihoods in the city context.

See Table B1.

Table B1
List of Urban Adaptation Assessment Indicators.

Hazard	**Sensitivity and Adaptive Capacity Indicators**
Flooding	Whether the city has climate vulnerability assessment on future flooding risks
	Whether the city has early warning system to communicate about upcoming flood hazards
	Proportion of manufactured/mobile home in city housings
	Proportion of city buildings that comply with the most recent building codes
	Proportion of impervious surface area
	Whether the city has Combined Sewer System (CSS)
	Proportion of city housing in flood zones
	Proportion of population with poor or fair health
	Proportion of uninsured population
	Percent of adults who needed to see a doctor but could not because of cost
	Cost of public transport
	Frequency of public transport use (Trips per capita)
	Proportion of the population within 1mile of public transportations
	Quality of drinking water
	Volume of water that treatment plant processes in 24 hours
Heat Wave	Whether the city has climate vulnerability assessment on future heat wave hazard
	Whether the city has early warning system to communicate about upcoming heat wave hazards, especially to vulnerable population.
	Consumption of electric resource (megawatt hour/customer)
	Selling price of electric resource (cent/megawatt hour)
	Proportion of housing units with air conditioning
	Tree canopy coverage
	Proportion of public buildings with air conditioning that can potentially serve as cooling centers when needed
	Proportion of population with poor or fair health
	Proportion of uninsured population
	Percent of adults who needed to see a doctor but could not because of cost
	Acute hospital beds (per 1000 people)
	Hospital outpatient emergency department visit rate (per 1000 people)
Drought	Whether the city has climate vulnerability assessment on future drought hazard
	Whether the city has early warning system to communicate about the upcoming drought hazard, especially to water-intensive industries
	Public awareness and media coverage on water scarcity
	Water stress (water supply compared with water consumption)
	Whether the city has water conservation program
	Whether the city uses policy instruments to regulate industrial water use and control water wasting

Appendix C.

Hazard Index Definitions and Model Identification.

See Table C1 and C2.

Table C1
Hazard Index Definitions.

Short name	Descriptive name	Proxy-hazard	Definition
rx5 day	*Monthly maximum consecutive 5-day precipitation*	Flooding	Monthly maximum precipitation observed over 5-day intervals
wsdi	*Warm spell duration index*	Heat wave	Number of days with maximum daily temperature above the 90th percentile, in spells of at least 6 consecutive days
cdd	*Maximum length of dry spell*	Drought	Maximum number of consecutive days in a year with less than 1 mm of precipitation

Table C2
Hazard index model identification.

Modeling Group	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC)
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence EC-EARTH consortium	CSIRO-QCCCE EC-EARTH	CSIRO-Mk3.6.0
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G GFDL-ESM2M
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	INM-CM4
Institut Pierre-Simon Laplace Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	IPSL MIROC	IPSL-CM5A-LR IPSL-CM5A-MR
Institut Pierre-Simon Laplace Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	IPSL MIROC MIROC	MIROC-ESM MIROC-ESM-CHEM MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-MR MPI-ESM-LR
Meteorological Research Institute	MRI	MRI-CGCM3
Norwegian Climate Centre	NCC	NorESM1-M

Please cite this article in press as: C. Chen, et al., Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas, Environ. Sci. Policy (2016), http://dx.doi.org/10.1016/j.envsci.2016.05.007

Appendix D.

Seattle's Adaptation Planning Document Used for Each Option.

See Table D1

Table D1
Seattle's Adaptation Planning Document Used for Each Option.

Adaptation Level	Adaptation Option	Primary Adaptation Planning Document Used
No-Regret Adaptation	Updating climate risk assessment on a regular basis	Seattle's Climate Action Plan
	Enhancing early warning systems to communicate about upcoming hazardous events	This adaptation option was ultimately identified as a gap
	Improving the overall health of population, especially the vulnerable population	This adaptation option required research outside of adaptation planning materials
	Increasing the affordability of health care services	This adaptation option was ultimately identified as a gap
	Increasing the accessibility of emergency medical facilities (emergency room, acute hospital bed etc.) especially for the low-income population	This adaptation option required research outside of adaptation planning materials
	Expanding green spaces, including tree canopy coverage, green roof, and green storm water infrastructures	Seattle's Climate Action Plan
	Guaranteeing quality of drinking water	This adaptation option required research outside of adaptation planning materials
Primary Adaptation	Improving accessibility of affordable electric resources for home cooling	Seattle's Climate Action Plan
	Improving accessibility of public buildings that are equipped with cooling facilities	This adaptation option required research outside of adaptation planning materials
	Increasing public awareness on water scarcity	Seattle's Climate Action Plan
	Reducing water stress through implementation of conservation programs	Seattle's Climate Action Plan and Seattle Public Utilities (SPU) 2013 Water System Plan
	Using policy instrument, for instance, water pricing, to regulate water usage and control wasting at industry level	Seattle's Climate Action Plan
Secondary Adaptation	Regulating the installation of vulnerable housing types like mobile or manufactured homes	This adaptation option required research outside of adaptation planning materials
	Making public transport cheaper, easier to access (closer to housing), and more frequent	Seattle's Climate Action Plan
Tertiary Adaptation	Retrofitting sewer system to separate from storm water (and other surface runoff) drains	This adaptation option was ultimately identified as a gap
	Relocating residents in floodplains to safer places	Seattle's Climate Action Plan and Seattle's All-Hazards Mitigation Plan
	Improving the capacity of wastewater treatment by increasing the volumes of water treated, moved, and reused through the treatment system	This adaptation option was ultimately identified as a gap

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Appendix E.

General Assessment of Option Investment Scale and Outcome Reversibility.

If applied to a different city, the gap analysis we present may prioritize options for other hazards into the secondary or tertiary adaptation categories, depending climate model certainty and projected hazard magnitude. Therefore, options for these hazards may require assessment in terms of their level of investment and irreversibility. Table C1 below provides this general assessment for all options, when applicable (Table E1).

Table E1
Investment Scale and Outcome Reversibility for Flooding, Heat Wave, and Drought Options The "+" sign stands for reversible or small-scale options. The "–" sign stands for options otherwise. The blank cells means the reversibility and the scale of the investment are difficult to distinguish.

Hazard	Adaptation options	Reversibility	Small-scale investment
Flooding	Monitoring flood risks and updating flood risk assessment on a regular basis	+	+
	Enhancing early warning systems	+	+
	Regulating the installation of vulnerable housing types like mobile or manufactured homes	+	+
	Increasing green space or/and improving green storm water infrastructures	-	-
	Separating sewer system from storm water (and other surface runoff) drains	-	-
	Improving the overall health of populations; reducing the proportion of population with poor or fair health, especially the elderly		
	Increasing the affordability of health care services		
	Relocating residents in floodplains to safer places	-	-
	Making public transport cheaper, easier to access (closer to housing), and more frequent	+	-
	Guaranteeing the quality of drinking water		-
	Improving the capacity of wastewater treatment by increasing the volumes of water treated, moved, and reused through the treatment system.	-	-
Heat Wave	Updating heat risk assessment on a regular basis, based on vulnerability assessment and future hazard projections	+	+
	Enhancing early warning systems, especially for vulnerable groups (e.g. the elderly population, those with poor health, low-income, etc.)	+	+
	Improving accessibility of affordable electric resources for home cooling	+	-
	Expanding green spaces, including tree canopy coverage, green roof, or other forms of urban forestry	-	-
	Improving accessibility of public buildings that are equipped with cooling facilities	+	+
	Improving the overall health of population, that is, reducing the proportion of the population with poor or fair health, especially the elderly		
	Improving accessibility of affordable health care service		
	Increasing the accessibility of emergency medical facilities (emergency rooms, acute hospital beds etc.) especially for the low-income population		
Drought	Updating drought risk assessment on a regular basis, based on water scarcity assessment and future hazard projections	+	+
	Enhancing early warning systems for water-intensive industries	+	+
	Increasing public awareness on water scarcity	+	+
	Guaranteeing the quality of drinking water		-
	Reducing water stress through implementation of conservation programs	+	-
	Using a policy instrument, for instance, water pricing, to regulate water usage and control wasting, especially at the industry level	+	+

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Please cite this article in press as: C. Chen, et al., Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas, Environ. Sci. Policy (2016), http://dx.doi.org/10.1016/j.envsci.2016.05.007

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Please cite this article in press as: C. Chen, et al., Measuring the adaptation gap: A framework for evaluating climate hazards and opportunities in urban areas, Environ. Sci. Policy (2016), http://dx.doi.org/10.1016/j.envsci.2016.05.007