5 Data and Analytics:
Meeting Forward-Looking Science Needs

Introduction

Two important mandates of AB 2800 are to consider and investigate:

1. The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design; and
2. The critical information that engineers and architects responsible for infrastructure design and construction need to address climate change impacts.

In this chapter we summarize what the Climate-Safe Infrastructure Working Group (CSIWG) found in terms of climate information currently used in infrastructure planning and design and what forward-looking climate science needs exist, along with barriers to using it. Throughout the discussions, the CSIWG identified other sources of forward-looking information beyond physical climate science. Those are presented here as well.

Identification of Climate-Sensitive Infrastructure

Perhaps the most important immediate outcome of AB 2800 is to demonstrate the State's commitment to understand the barriers that until now have limited agencies' ability to incorporate forward-looking climate information.

Following the mandate of AB 2800 and using the ASCE (2015)[178] report recommendations, the CSIWG identified the infrastructure that should be addressed as part of this study. It then assessed the information required to implement existing standards, guidelines and regulations, which determine how infrastructure is planned, designed, built, operated and maintained. Working Group members also identified relevant standards that come into play in building and maintaining infrastructure. Only those codes, standards and guidelines that cannot accommodate a changing climate must eventually be updated with forward-looking climate information (for a fuller discussion see Chapter 7). While some State agencies have begun to do so, not all have.

CSIWG discussions focused on State-owned, -funded and -regulated infrastructure in the building, energy, water and transportation sectors (with an emphasis on infrastructure for which members had expertise), with lesser attention to infrastructure such as correctional and healthcare facilities, State parks and related green or nature-based infrastructure.[1] CSIWG members identified which weather/climate impacts their respective infrastructure assets currently face and those they expect to face more of in the future (Table 5.1).

One of the most important immediate outcomes of AB 2800 is to demonstrate the State's commitment to understand the barriers that until now have limited agencies' ability to incorporate forward-looking climate information.

[1] For the purposes of this report, we use a very broad definition of green infrastructure that can include both already existing or restored natural features, such as beaches, wetlands or habitat corridors, as well as human-made but nature-based infrastructure that is intended to serve a protective function or provide other ecosystem services to a community such as storm water management, groundwater recharge or greater tree cover in urban areas.

Table 5.1 CSIWG-Identified Climate Impacts to Assest Categories For Each Sector

Sector	Asset Category	Temperature		Wildfire		High Winds		Precipitation		Flooding/ Run-Off		Debris Flow / Mudslides		Coastal Flooding / Waves / Storm Surge		Sea Level Rise		Erosion		Drought	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Transportation	Culvert Design	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Transportation	Pavement Design		✓	✓				✓	✓	✓	✓			✓		✓					
Transportation	Bridge Design	✓	✓				✓	✓	✓	✓	✓		✓		✓		✓				
Transportation	Signal & Signage Design	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓				✓				
Transportation	Caltrans Buildings	✓	✓	✓	✓				✓	✓	✓										
Transportation	Safety Rest Areas	✓	✓	✓	✓					✓	✓										
Transportation	Landscape Areas	✓	✓	✓	✓			✓	✓		✓									✓	✓
Transportation	Roads & Bridges	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				
Transportation	Rail System & Busways	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓								
Transportation	Bust & Rail Mainte-nance	✓	✓			✓	✓	✓	✓	✓	✓										
Transportation	Electrified Fleet	✓	✓			✓	✓	✓	✓												
Transportation	Rail Cars & Buses	✓	✓																		
Transportation	Ports					✓	✓	✓	✓	✓	✓			✓	✓		✓				
Transportation	Coastal Roads & Railroads					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Energy	Hydro Dams							✓	✓	✓	✓	✓	✓				✓		✓	✓	✓
Energy	Power Plants		✓					✓	✓	✓	✓	✓	✓		✓		✓		✓		✓
Energy	Electrical Transmission Lines	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓		
Energy	Electrical Transformers	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓		
Energy	Natural Gas Compressor Stations	✓	✓							✓	✓				✓		✓		✓		
Energy	Natural Gas Pipelines														✓		✓		✓		✓

Table 5.1 (Con'd) CSIWG-Identified Climate Impacts to Assest Categories For Each Sector

Sector	Asset Category	Temperature		Wildfire		High Winds		Precipitation		Flooding/ Run-Off		Debris Flow / Mudslides		Coastal Flooding / Waves / Storm Surge		Sea Level Rise		Erosion		Drought	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Buildings	Energy Demand for Space Cooling	✓	✓																		
Buildings	Energy Demand for Space Heating	✓	✓																		
Buildings	New Buildings	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
Buildings	Existing Buildings	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
Buildings	Parking Lots	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
Buildings	Garages	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
Water	Dams			✓	✓			✓	✓				✓								
Water	Pipelines / Tunnels							✓	✓	✓	✓	✓	✓	✓					✓		✓
Water	Canals	✓	✓					✓	✓		✓						✓		✓		
Water	Levees					✓		✓		✓	✓			✓			✓				
Water	Sewage Treatment Plants							✓	✓	✓	✓			✓	✓		✓		✓		
Water	Sewage Pipes / Septic Fields							✓	✓	✓	✓			✓	✓		✓		✓		
Water	Pumping / Generating Plants	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓		✓		✓

It is immediately apparent from Table 5.1 that the impacts of temperature, wildfire and high winds, as well as the combined impacts of precipitation and associated flooding present immediate challenges to existing infrastructure, and these are expected to be exacerbated with a changing climate. Impacts from sea-level rise, coastal flooding and coastal erosion are important in specific locations where critical infrastructure is located along the coast.

Information Currently Used for Infrastructure

Fulfilling the mandate of AB 2800 to identify information needs and any barriers to information uptake requires: (1) an understanding of the information that is currently available and that is regularly being used by engineers and architects now; (2) identifying the perceived gaps in currently existing information; and (3) identifying future climate-science (and other forward-looking science) needs. Appendices 4 and 5 provide summaries of the information currently used in infrastructure design and maintenance and identify future climate-science needs broken out by infrastructure sector. These tables in the appendices belie the complexity of the conversations, however, about what information is really needed and the level of detail required to continue to decrease risk in infrastructure design, planning and implementation. We address this greater complexity in the sections below.

Forward-Looking Climate Science Needs

Chapter 2 of this report identified what is currently understood about climate trends and projections into the future. However, engineering studies and planning often require information at a parcel- or project-level scale, and at time scales not always currently available from global climate projections (e.g., precipitation rates on an hourly scale versus monthly or annual averages). If that level of detailed information is available, it is usually accompanied with high degrees of uncertainty and wide ranges of possible future climates, which are themselves dependent on the even less predictable behavior of humans and future global greenhouse gas emissions. This disconnect between what is available and credible on the one hand and what is needed by engineers and architects on the other has stymied much effort to incorporate forward-looking climate information into existing design standards, guidelines and principles.

The CSIWG does not believe, however, that this disconnect creates an unworkable impasse. Instead, the CSIWG identified an adaptive process by which infrastructure planning can continue with the information that is currently available, while also highlighting climate information needs that would be useful moving forward. This entails using the information that is currently available, while allowing for more refined information to be incorporated in the future (see the adaptive pathway described in Chapter 4); when possible, using adaptive designs for planning infrastructure (discussed more fully below); while developing sustained funding source to advance climate and social science as well adaptive engineering research to fill identified gaps (see research needs below and in Chapter 8). To prioritize achieving this latter step, the CSIWG identified critical information needs for each sector (Appendices 4 and 5). Table 5.2 provides selected examples of some of the information needs – typically requiring additional research to fill them – while Appendices 4 and 5 provide a more complete list for each sector.

Figure 5.1 An important component to adaptive design entails monitoring and observing how the infrastructure responds to current environmental conditions, as well as monitoring global emissions, how climate is reponding and whether adjustments are needed to ensure existing infrastructure is climate-safe (see also Chapter 9) (Photo: U.S. Army Corps of Engineers)

As we highlight these climate information needs, it is important to recognize that most of these data are already available, just not at the level of granularity thought to be needed by the engineering community. Where the desired granularity cannot be obtained, decision-analytic frameworks such as decisions scaling[146,206-208] and robust decision making (see Chapter 6) can be used to arrive at climate-safe infrastructure designs despite lack of adequate or uncertain data. In fact, many of the forward-looking climate data needs are in fact climate research – and research capacity – needs. For instance, the CSIWG called for more detailed information on increased capacity to model precipitation and storm water flows in urban areas in a changing climate. There has been some pioneering work in this area by CSIWG members and other researchers[56,58,209-213], however most studies are limited in geographic scope and require time and investment to apply to other locations (see Chapter 2 and Box 5.1 below). Detailed analysis of the concurrence of different flood contributors is equally time- and resource-consuming[56]. Thus, research is needed to identify less computationally-expensive methods to develop these flood projections; this is, in turn, dependent on funds to ensure adequate research capacity.

The perceived lack of sufficiently high-resolution data and too much uncertainty in the projections already available may not be solved by more research, but rather requires a new approach to planning and design. The CSIWG accordingly grappled with the consistent challenge of ensuring that "the perfect not become the enemy of the good." The applied research question then becomes: where is the higher-resolution information actually needed and when/where does this higher level of resolution imply a false sense of precision about what we can expect in the future? Can infrastructure systems be designed to be adaptive and be able to withstand a range of possible climate futures, rather than be tied to one particular future, which may or may not ever become reality. In Chapter 6, we will discuss probabilistic risk management and adaptive design approaches, and in Chapter 7 ASCE's Manual of Practice. Both provide concrete steps by which engineers and architects can do exactly this.

The perceived lack of sufficiently high-resolution data and too much uncertainty in the projections already available may not be solved by more research, but rather requires a new approach to planning and design.

Table 5.2: Examples of Forward-Looking Climate Information Needs, Requiring Additional Research, for Selected Infrastructure Sectors (see also Appendix 5)

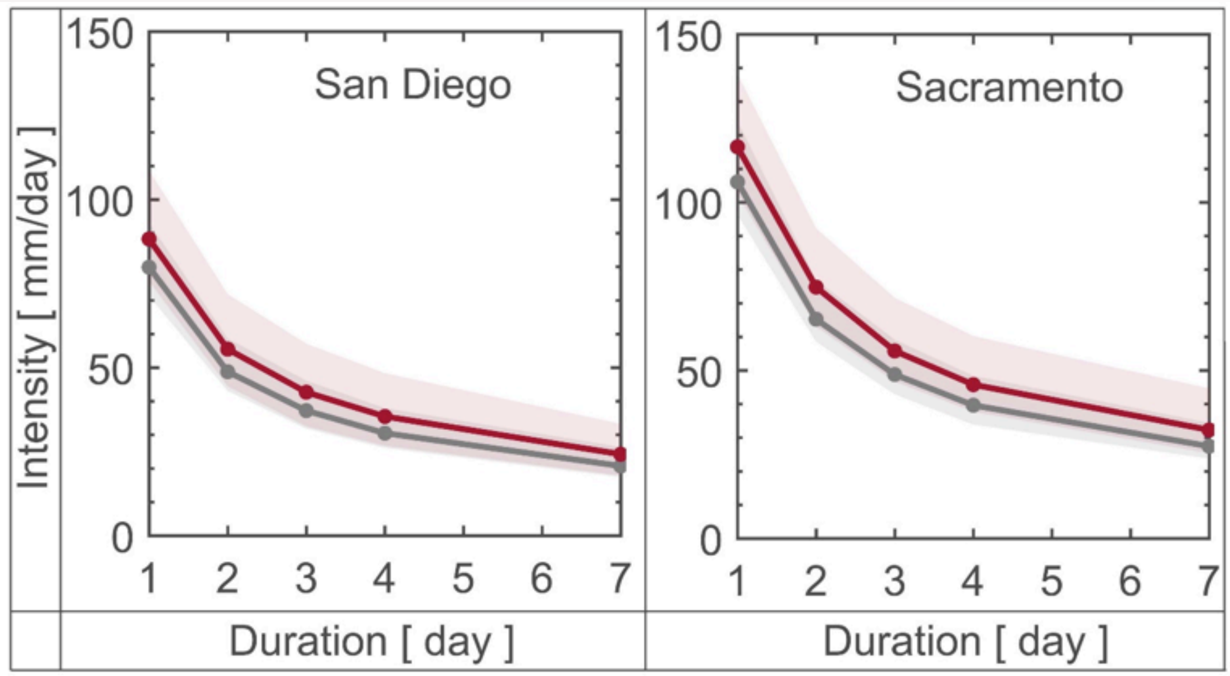
Water Infrastructure • Flow rate (hourly) data for urban water systems • Increased capacity to model flow in urban areas • Continuous and reliable runoff information • Sub-hourly precipitation measurement • Spatial/temporal resolution (varies for different types of infrastructure and depends on size/scale)
Transportation • Rain intensity, downscaled to highest spatial resolution possible • Sea level rise downscaled to highest spatial resolution possible • Extreme wind prediction • Change in storm surges • Change in temperature • Frequency of extreme temperatures • State developed flood plain maps • Regional maps identifying areas susceptible to wildfires (i.e., infrastructure within areas susceptible to wildfires) • Regional maps identifying areas susceptible to mudslides (following wildfires)
Energy/Buildings • Downscaled global climate model data at smaller temporal scales (i.e., from daily [6 hour] to hourly data needed for building energy modeling [e.g., dry/wet bulb temperatures, solar radiation, wind speed and direction]) • Sea-level rise impacts on groundwater levels • Different spectrums of radiation for material and surface light of building components • Future projections and variability of outdoor air quality

Box 5.1: Example of How to Fill Specific Climate Science Needs

Experts at the University of California, Irvine, have prepared rainfall Intensity-Duration-Frequency (IDF) curves using projected precipitation data. These projected precipitation IDF curves have been prepared for 14 major cities in California[58]. Members of the CSIWG noted that forward-looking IDF curves need to be developed for the entire state. Such IDF curves are used in design of storm water systems, levees, bridges, culverts, etc.

At present, IDF curves are based on historical data, using data tables from NOAA Atlas 14. Not having IDF curves for future climate conditions limits incorporation of climate change into the design of these types of infrastructure. Data would need to be developed at a resolution of 0.06 degree (dividing the state into ~11,800 grid cells). This would amount to having data representing 3 to 4-mile square cells statewide. To complete this task could take 1-2 years and additional resources but is entirely achievable and would benefit water and transportation agencies and other State agencies for design and planning projects.

A recent paper[214] assessed how out-of-date state design manuals are, given extreme rainfall occurrences and projected changes in extremes. It shows that California is one of eight states where updates of this sort should be a high priority.



IDF curves using forward-looking climate projections (RCP 8.5, red curve) for a rainfall event in San Diego (left) and Sacramento (right) that has a 25-year recurrence interval), with a 90% confidence interval (pink-shaded area), compared to the historical IDF curve (black curve) (Source: Adapted from Ragno et al. 2018[58]; used with permission)

Beyond Climate Science Information

While the scope of AB 2800 can be read to be limited to physical climate science information, the phrase “climate impact science” opens up a much larger body of work, ranging from physical impacts to ecological and social impacts. In the course of the CSIWG’s deliberations, many other information needs were identified that extend beyond traditional climate, geophysical or meteorological information that are not even just “impacts science.” These data needs spanned from traditional social scientific information such as projections of future land use, demographics and social vulnerabilities, to the economics of adaptation and cost-benefit analyses of different infrastructure concepts and plans (which then ultimately drive final design decisions), to shifting infrastructure technologies and associated energy demands as communities electrify transportation and move from fossil fuel-based energy sources to renewables throughout California. Such information is as critical to making infrastructure decisions as climate information: if future transportation is electrified, how and where should charging stations be built to be safe from climate impacts? If the energy system is reliant on a greater share of microgrids and distributed energy sources, should existing energy infrastructure be retrofitted or decommissioned? And so on.

Land Use, Demographic, Socioeconomic and Ecological Information

Many types of critical infrastructure have a 20 to 30-year design life cycle, with a useful life that can extend an asset’s life for several more decades if it is well maintained and built appropriately. The communities dependent on, and hosting, these long-lived assets can – and do – change dramatically over these years. In California’s major urban centers, urbanization continued unabated, involving rapid population growth with concomitant increased economic activity – albeit with increasing income disparities, gentrification, housing costs and homelessness. Conversely, in the early 2000s, a number of communities went bankrupt or experienced serious declines in their budgets, either due to population declines, shifts in the economic bases, the 2007-08 recession or other fiscal challenges (e.g., in California, the City of San Bernardino and City of Stockton had to declare bankruptcy). As urban sprawl continues its growth along the edges of the major metropolitan regions, land use patterns shift and infrastructure needs and vulnerabilities change[215-217]; J. Thorne presentation to the CSIWG, 2018). If income disparities persist or increase further, the number of people living below the poverty level would increase (see the equity profiles highlighted in Chapter 4). These economic disparities are a key contributor to social vulnerability. Implementation of the Climate-Safe Path for All, as argued in the previous chapter, should be informed by such socioeconomic data as much as by climate data.

When determining whether to retrofit existing or build new infrastructure such social and economic data points must be considered. However, reliable projections of land use, population growth and economic activity are inadequately understood (as discussed in Chapter 3). Climate change also causes significant (and uncertain) change in the environment. However, major infrastructure projects must mitigate their impacts on the environment and thus need reliable ecological information to inform those environmental mitigation efforts (J. Thorne presentation to the CSIWG 2018). In the past, California has supported some research that has considered various interactive (social, physical and ecological) drivers of climate impacts[84,218], but more such work is needed to cover all of the state.

Figure 5.2: As urban sprawl continues its growth along the edges of California’s major metropolitan regions, land use patterns shift and infrastructure needs and vulnerabilities change. Planning climate-safe infrastructure should be informed by forward-looking socioeconomic data as much as climate data. (Photo: Interstate 805 in San Diego, Wikimedia Commons, licensed under Creative Commons license 2.0).

Recommendation 2

In the past, the State's financial support for its various climate science efforts and decision-support tools has been uneven and insufficient. At a minimum, the State Legislature should provide a permanent source of funding for the State's mandated Climate Change Assessment process, the State's ongoing Climate Change Research Program, and decision-support tools and other assistance that disseminate their findings, so as to meet the needs for improved understanding and forward-looking science information.

There are several critical next steps that the State can take to operationalize Recommendation 2 and fill the identified information/research gaps and place California's climate research and assessment efforts on a stronger foundation (see also Table 5.2 and Appendices 1-2):

1. The State should convene a follow-up panel or process to prioritize the full range of information gaps (bio-physical, engineering, and socio-economic) identified by the CSIWG into high, medium and low priority. For those gaps identified as high priority, the State budget should provide a level of funding and staffing commensurate to fill these gaps—utilizing resources both internal and external to State government – within five years, where scientifically feasible. State agencies should furthermore establish formal and readily implementable guidelines at the agency/programmatic level and at the project level as to what it means to "incorporate climate change" into infrastructure planning, design, construction, operation and maintenance. This guidance should rely on the concepts and suggestions made in this report.
2. With the help of the Strategic Growth Council, the Natural Resources Agency and the California Energy Commission, future renditions of the Climate Change Research Plan should prioritize research needs identified in this report, including identification of the most appropriate agency and outside partners capable of addressing them, and look at all relevant climate, emergency planning and infrastructure-specific funding sources to support these needs.
3. For water infrastructure information needs in particular, the Department of Water Resources (DWR), working with other State agencies as well as a diverse group of stakeholders, has recommended formally establishing and funding a California Climate Science and Monitoring Program in the *Draft California Water Plan Update 2018*. Should this finding be included in the final version of the 2018 update, the State should implement and fully fund this recommendation.
4. The State Budget should provide modest and stable additional funding to expand the State Climatologist Office, in order to realize the full potential of the State Climatologist to engage the climate science community and in turn advise State government on climate change issues.

5. The State need not begin from scratch, but rather can leverage and expand on already ongoing (and in some cases, state-funded) research throughout the state by both public and academic researchers to ensure forward-looking climate science is available at high resolution for use by state and regional or local infrastructure owners. With expected benefits to various State agencies and to projects across the state, the Legislature should provide funding for research in the following areas:
    (a) Produce statewide IDF curves with associated uncertainty for future climate conditions (especially the high-emissions scenario, to be consistent with the Climate-Safe Path for All described in Chapter 4);
    (b) Continue to invest in high-resolution climate modeling to better define spatial and temporal structure of extreme events;
    (c) In addition to studies focusing on future projections, traditional knowledges and paleoclimatology should also be included as funding priorities;
    (d) Building on the State's previous investment in USGS's CoSMoS model for sea-level rise and storm surge, determine where exactly in the state even more fine-scaled hydrodynamic modeling is needed and focus additional resources there; and
    (e) Because extreme events are particularly critical to climate-safe infrastructure design, invest in research that merges case studies, ensemble modeling, forecast experiments and sophisticated uncertainty analysis approaches to investigate the likelihood, mechanisms, joint probabilities, predictability of climatic extremes, including worst-case events, that pose significant threats to California's infrastructure.

In order then to further implement Recommendation 2, the CSIWG identified critical social science information needs that should be filled through State agency-supported research and in partnership with external experts. Some of this information may be available in existing academic research but is not widely known or available to infrastructure planners and familiarity with such information is often lower than with physical science information:

1. Fine-spatial scale historical demographic information to identify vulnerable populations and to more fully understand the factors that drive social vulnerability;
2. Fine-spatial scale historical information on infrastructure use and detailed understanding of the factors that drove those use patterns;
3. Transit-dependent population information;
4. Projections of demographic shifts under different economic and climate conditions;
5. Projections of climate change impacts (e.g., ecological) that combine climate, economic, demographic and other drivers; and
6. Projections of changes in technology and infrastructure use (e.g., electrification and related changes in energy infrastructure needs and energy use).

Adaptive Design and Related Economic Analyses

With climate change, the impacts that infrastructure will have to withstand will change over time, but both the rate and extent of change are uncertain. Most infrastructure incur a large upfront cost that is fixed and sunk. It is fixed in the sense that it is required even before any usage can begin. A highway needs to be built before anyone can use it. It is sunk in that once built, one cannot really recoup this cost by selling it. Once a highway is built, the concrete cannot easily be repurposed for something else that has value. Because of these features, most standard infrastructure projects are not very flexible. They are built for a particular design requirement and cannot easily be adjusted if requirements change in the future.

As we discuss in this report, however, there are a number of ways to ensure even during construction that infrastructure can withstand future conditions, which cannot be fully known. Traditionally, designers required infrastructure to be built with "safety buffers" (see Chapter 3). For example, if sea level is projected to rise 1 ft by the middle of the century but there's a 10% chance it rises by 2 ft, the uncertainty could be addressed by requiring a structure to be built with a 2 ft clearance. This is costly as it is building for a lower-probability event but, if it occurs, can be a high-impact event. An alternative approach is to require that infrastructure is built with some degree of modularity so that it can be adaptively adjusted in the future, if needed. In the example above, engineers could design the highway today such that it meets the near-term needs of accommodating just 1 ft of rise, but has the option to build it higher in the future if the 2 ft rise becomes reality. This might involve a stronger base to elevate protective measures or the ability to raise the structure or space to move it back (Figure 5.3). In the first (safety buffer) approach, infrastructure is fixed now to deal with the "worst case" of what is known about the future today. In the second (adaptive) approach, infrastructure is built in a modular fashion to allow for adjustment if it becomes necessary at some point in the future.

Neither adaptive design choices in different infrastructure sectors nor cost estimates of these options – compared to traditional design choices – are well understood at this time. While the shift in this direction has begun (B. Ayyub, presentation to the CSIWG 2018; see also discussion in Chapter 6), questions arise as to whether traditional cost-benefit analyses adequately capture the value gained for such construction, despite potentially higher initial cost outlays (see Chapter 8). How to incentivize adaptive design approaches is insufficiently understood and there is still a paucity of research on what cost-benefit methodologies

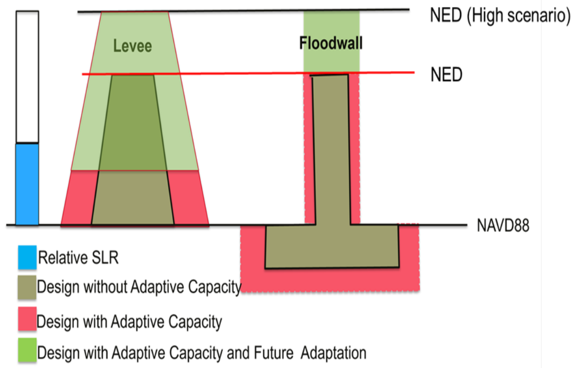


Figure 5.3: Cross sections of a levee and a seawall built with foresight and adaptive capacity so that the protective structures can be enlarged in size later if or when sea-level rise requires additional protection. (Source: Kate White webinar 2018, USACE)

might be best. Research is therefore needed to improve economic models and cost-benefit analysis methodologies to better model the true life-cycle costs of adaptive design. This may entail a paradigm shift as future resilience is not currently prioritized in traditional analyses.

More fundamentally, there are profound knowledge gaps as to how much it might cost to adapt California's infrastructure to the changing climate. The State should invest in economic research to better understand the growing fiscal risks (and opportunities) from climate change impacts and adaptation, particularly in the context of an integrated infrastructure investment strategy (Chapter 8).

Tools, Platforms and Processes to Support the Exchange between Scientists, Engineers and Architects

AB 2800 mandated that the CSIWG review and include recommendations on tools and "a platform or process to facilitate communication between climate scientists, infrastructure engineers [and architects]." CSIWG members discussed their experiences with existing tools, platforms and processes, the strengths and weaknesses of those, and what they see as the most useful path forward for the State.

Existing Efforts

The CSIWG emphasized the importance of recognizing that there is already ongoing work at various State agencies to facilitate discussion among climate scientists, engineers and architects. During in-state conferences, California's climate change assessments and research activities, professional association meetings (e.g., annual meetings of the American Geophysical Union (AGU), which in the past were regularly held in San Francisco) and in other venues and activities, state engineers have actively engaged with climate scientists for many years. In turn, these exchanges have informed the direction and usefulness of climate science for practicing engineers. While difficult to measure, such interactions have led to the formation of lasting and valuable personal relationships and the creation of trust between individual climate scientists and state engineers, providing for informal, two-way consultation on a variety of scientific matters (Box 5.2). Within California, state engineers have also worked closely with state-based climate researchers in several research studies included in the Fourth Assessment (see also Chapter 2), and such collaboration in future research and assessment activities should be continued and enhanced, starting with the development of user-oriented research agendas to ensure that the science that gets funded fits the most pressing state needs.

State agencies also have made dedicated efforts to bring together climate scientists and state engineers for focused projects and outcomes. For instance, DWR has twice formally assembled a Climate Change Technical Advisory Group (CCTAG), the first to specifically advise the *California Water Plan Update 2009*, and the second – which involved CSIWG member, Dr. Dan Cayan, and Project Team member, Guido Franco – to provide advice on the use of planning approaches and analytical tools in DWR project management. In 2015, this collaboration, chaired by DWR climate scientist Elissa Lynn, produced a widely cited final report, *Perspectives and Guidance for Climate Change Analysis*[219], which directly informed the state's Fourth Climate Change Assessment[220]. This process of bringing together scientists and engineers was also the subject of a poster at the AGU meeting in 2016 (Appendix 6).

Yet, while DWR's CCTAG is an excellent example of interdisciplinary coordination, these types of efforts are still not commonplace, largely because they require significant resources (money, time and people) and sustained commitment from the lead agency and the participating scientists to ensure a continued effort and actionable outcomes. Moreover, the purview of the CCTAG was focused on just one sector; but this level of effort needs to be replicated across all critical infrastructure sectors (transportation, energy, buildings, telecommunications etc.) in order to advance climate-safe infrastructure across the State's assets.

The challenge is also bigger than "simply" bringing together climate scientists, engineers and architects. Throughout the CSIWG's discussions, it became evident that big sources of uncertainty or lack of knowledge are not only about climate change but are related to the subject matters of other disciplines, such as economics, land use, demographics and behavioral science as discussed above. Similarly, discussions on policy design, governance, implementation of new methods through workforce development and training, and concerns of ensuring social equity, are also critical to the discussion. Thus, there may not be a single platform or process, and for any to be effective, the engagement must include representatives from all of these disciplines and areas of expertise. It will take time for participants to understand each other's language and concerns, thus sustained efforts will actually be more cost-effective than one-off engagements (Box 5.3).

Box 5.2: Unsung Heroes

While mostly unsung, there is a long and rich history of the state's engineers communicating and working with climate scientists. In 1987, Mr. Maury Roos, Chief Hydrologist for DWR, presented a paper entitled "Possible Changes in California Snowmelt Patterns" at the Fourth Pacific Climate (PACLIM) workshop in Pacific Grove, California – one of the early investigations into the effects of a changing climate on California's water resources. Another example is Guido Franco, a licensed mechanical engineer with the California Energy Commission (CEC). Mr. Franco has played a major role in each of the state's four climate change assessments (2006, 2009, 2012 and 2018), mandated by former Governor Schwarzenegger's Executive Order S-3-05. State engineers, including Mr. Franco, are also members of the editorial board for California's Fourth Climate Change Assessment. Mr. Franco is a key contributor to the state's Climate Change Research Program, as is Dr. Michael Anderson, a licensed civil engineer with DWR, who also serves as California's official State Climatologist.

Clockwise from left; Marty Ralph, Scripps Institute of Oceanography, Michael Anderson, State Climatologist with DWR, Jay Jasperse, Sonoma County Water Agency, and Jeanine Jones, Interstate Resources Manager at DWR, during a break at an October 2016 workshop on drought vulnerability in southern California. (Photo: Kelly M. Grow, DWR, used with permission)

Box 5.3: California and the Sustained National Climate Assessment Process

During the development of the Third National Climate Assessment (NCA3, delivered in 2014), a new concept was developed – namely, the idea of a sustained national climate assessment[221]. The idea of a sustained assessment was in part a response to the "stop-and-go" approach to previous national climate assessments, mandated by federal law since 1990 to be delivered to Congress every four years, but for a number of reasons not delivered with this regularity[222]. At the same time, many information users and decision-makers increasingly ask for state-of-the-art data and usable, actionable knowledge syntheses, which were not being delivered through the national assessment reports.

Since then, the notion of a sustained assessment has been significantly developed further (see also Moss 2018 webinar). While assessments in California typically involve the production of new research, more commonly assessments serve to synthesize existing science and critically assess the state of knowledge so as to provide reliable guidance to decision-makers on what is well understood and what is less well known at a given point in time (examples of this approach include the NCA and the IPCC assessments).

The sustained assessment idea (although still evolving) describes an ongoing platform for interactions between researchers and science users, drawing heavily on partnerships of federal agencies, research institutions, science-based non-governmental organizations, professional societies and others to provide knowledge syntheses and assessments that are driven by user needs. If traditionally assessments focused only on the state of science, a sustained assessment could also include assessments of the state of practice that is of interest to practitioners (e.g., to support the search for innovative or best practices). Similarly, the traditional sector or regional focus could be augmented with an emphasis on implementation challenges (such as updating codes, assessing financial risks of different adaptation approaches or design challenges).

California could greatly benefit from actively participating in shaping and implementing the sustained assessment process. Opportunities include the following:

- **Active participation in the sustained assessment process:** As the sustained assessment consortium of civil society and State/local/tribal groups is launched, California should be actively represented in the consortium and process. The consortium will identify, develop and evaluate sources of reliable, relevant and actionable information to support action, and to contribute to integration of knowledge and scientific understanding. California will benefit both from ensuring its own research is included, thus illustrating its national leadership, and from learning from the work done by others.
- **Convene sustained conversations (e.g., communities of practice involving scientists, engineers and architects) about the challenges, opportunities and benefits of applying climate change science (broadly defined) in infrastructure design:** This could also involve direct engagement with professional societies to ensure a direct link into entities that shape standards and guidelines at the national level.
- **Foster innovation in the applied science/engineering community:** As this report shows, the engineering community is not only challenged to adopt new scientific information into its traditional ways of doing things, but – over time – to transform its ways of doing business. There are many dimensions of these novel practices and engineers and architects across the nation can and should learn about and from them. The sustained assessment process is one way to track and share innovative practices initiated in California and elsewhere.
- **Improve linkages between state-level assessments and NCA reports:** Many states are undertaking their own assessments, but when they are not aligned in time with the national assessment report cycles, much of what is being learned at the state level is not shared nationally and vice versa.[2] Thus, coordinating timing, ensuring regional representation and reducing overly burdensome demands on researchers participating in both assessments would improve state-national assessment linkages.

[2] California's Fourth Climate Assessment is concluded and released publicly one month after the deadline for inclusion of papers in the Fourth National Climate Assessment, resulting in hundreds of thousands of dollars of State-funded research not being able to be included in the NCA4. The Fourth Assessment reports that were accepted for publication prior to June 15 and personally brought to the attention of NCA4 author teams are an exception.

What Makes Platforms Successful?

Based on a literature and web review and meeting discussions, the CSIWG identified the following five interconnected criteria that both build on each other and are equally critical to developing effective science-practice processes in support of building climate-safe infrastructure.

1. **Establishing clearly defined goals and priorities.** Before commencing discussion via any means (tools, process or platform), the CSIWG felt that the critical first step is to identify the goals and priorities for the discussion and to have these bounded by specific outcomes. Working Group members agreed that any effort to create a Climate-Safe Infrastructure platform should have one or more specific products to work towards (see, e.g., discussion on a California-specific Manual of Practice below).
2. **Engaging the right participants.** The CSIWG highlighted the importance of careful curation of platform participants and discussants. Experts from various disciplines must be included, as well as participants who are knowledgeable on the technical or practical details as well as those who can work well across areas of expertise and who can help facilitate conversation (these might not always be the same people). It is also important to ensure that all participants recognize that they both contribute to and get something out of the process (see discussion below on continuing the work of the CSIWG).
3. **Sustaining a deliberative process and the funds to support it.** Identifying the process and requirements for developing climate-safe infrastructure is not something that can be accomplished in a handful of sporadic, ad-hoc meetings. The science is ever-evolving as are engineering methodologies. Thus, as goals are set, consideration of the timeline required to meet those goals should be commensurate. For ultimate success, these discussions must also include a sustained source of funding, which is especially important to ensure equitable social inclusion and participation for all relevant voices (see social equity discussions in Chapter 4 and implementation needs in Chapter 9).
4. **Being able to form robust and trusting relationships.** In the most successful examples, CSIWG members identified the development of trust among participants one of the most important components of successful collaboration, resulting in useful products and outcomes. This requires having the opportunity to engage with others on a consistent basis for a specified period of time, which will likely require commitment of funding from agency budgets, NGOs, philanthropic organizations, private sector, professional or academic societies, or ideally some combination of all (Figure 5.4).
5. **Prioritizing transparency.** Transparency builds trust. To many engineers, climate models are black boxes they do not understand. To many scientists and non-governmental outsiders, the same is true for government decision-making processes. As a result, data and decisions are suspect and less likely to be used or accepted. Transparency and trust-building in the co-creation of actionable scientific information for application in infrastructure design and planning is thus a critical pre-condition for use of data and tools.

The success of the DWR CCTAG example described above highlights many of these criteria[220]. DWR prioritized this work and provided some financial support via travel stipends for CCTAG members. The CCTAG members were also committed to the process and were willing to donate their time and effort to help advance the goals of the group, which were well-defined from the inception. Additionally, DWR highlighted the identification of the “right” mix of experts who developed a trusting relationship due to the sustained nature of the effort, which spanned three years.

The Working Group reviewed a number of existing platforms that have the goal of linking science to practical applications. Examples are shown in Table 5.3, yet none resolve the challenges discussed during the CSIWG deliberations. There was consensus among the CSIWG that continued opportunities for scientists, engineers and architects to interact was critical to advancing climate-safe infrastructure in California, but that development of a new platform was not necessary. Indeed, the CSIWG preferred building on existing platforms that could be bolstered to include dedicated time, effort and funding to address the recommendations identified in this report.

Figure 5.4: Developing trust among diverse participants with different types of expertise and knowledges is one of the most important components of successful collaborations. (Photo: DWR, used with permission)

Table 5.3: Sample of Platforms Available for Exchange Between Scientists, Engineers and Architects

Data portals • Cal-Adapt • USGS Coastal Storm Modeling System/Our Coast Our Future • Climate Model Intercomparison Project (CMIP) • WeatherShift™
Tools platforms • Digital Coast • Resilience Toolkit
Interactive forums • Thriving Earth Exchange • Resilience Dialogues • Professional Society Meetings (e.g., AGU, ASAP, ASCE regional meetings) • California Adaptation Forum • National Adaptation Forum • National Academy of Sciences – Disasters Roundtable
Interactive forums • California Adaptation Clearinghouse • Georgetown Climate Center Adaptation Clearinghouse

While there are an increasing number of scientists who speak at professional society meetings and practicing engineers and architects who address scientific audiences, the CSIWG did not find any standing science-engineering/ architecture platforms dedicated to addressing the infrastructure design challenges arising from climate change. Some of the data portals and platforms listed in Table 5.3 were not known to or are not regularly (if at all) frequented by engineers and architects, including Cal-Adapt. Thus, they should be viewed as opportunities that could be used to foster better and more frequent interactions across the science-practice interface. In addition, scientific data must be brought to those data portals that engineers and architects already use.

One example is to make better use of the California Adaptation Forum (CAF). That conference already attracts local and regional practitioners as well as a range of consultants grappling with many of the climate adaptation considerations the CSIWG discussed, but engineers, architects and climate scientists do not attend that event in significant numbers. Similarly, practitioners on their part, do not usually attend the technical conferences generally convened by professional societies and academic organizations. Yet, as witnessed by the important discussions elicited during Working Group meetings and webinars that engaged a wide range of external experts with deep experience of working on the ground – this type of transdisciplinary dialogue is needed and critical. During future CAFs, the State could hold workshops specifically focused on discussions among state engineers and architects, physical and social climate scientists, local practitioners and professional societies to increase such transdisciplinary interactions and exchanges.

Deliberate, enhanced and sustained engagement of scientists with professional societies is a critical area on which to focus.

Deliberate, enhanced and sustained engagement of scientists with professional societies where engineers and architects already gather is another area on which to focus. Sharing the experience and process as well as outcomes of California's CSIWG will be of great interest to professional societies and other states. As we described in Chapter 1, this type of engagement has begun during the life of the CSIWG, but should be sustained and deepened over time.

Tools in Support of Climate-Safe Infrastructure

In response to the AB 2800 mandate to "consider and investigate the information and institutional barriers to integrating projected climate change impacts into state infrastructure design," the CSIWG also discussed available tools – both throughout California, as well as nationally and globally – that provide climate science information. Tools identified during Working Group meetings and through external data-gathering are listed in Appendix 5.

There are indeed many tools that have been developed that aim to connect practitioners to climate science, with the hope of advancing climate adaptation. As with the discussion on platforms and conferences from the previous section, however, these tools may not be the ones that state engineers and architects are likely to use. Moreover, there is at this point an overabundance of different types of tools that are variations of each other, with slightly different intended audiences and information. For instance, K. Baja pointed out during the webinar on tools that there are 4,300 green infrastructure tools and resources available to practitioners. Additional common challenges with regard to tools include:

- Most practitioners are unaware of available tools;
- Tools are ill-designed, difficult to use and there is typically no online or in-person support available to help practitioners use the tools effectively;
- Tools do not meet the specific needs of users (e.g., answer cost of action/inaction questions);
- Information available through tools does not connect to existing processes or reporting requirements;
- Tools do not help practitioners address real-life complexities;
- There is no way of knowing which tools are reliable or preferable to use over others; and
- Tools are for single purposes, without helping practitioners connect to the next step in the planning or design process.

While there remains considerable discussion on which data are available and if they are at the right scale for engineering projects (see Chapters 2 and 3), there was consensus among the CSIWG that development of new tools that are specifically focused on the climate science/engineering interface is not necessary, and maybe not even desirable. Rather, CSIWG members felt that existing tools could be modified and/or expanded to incorporate the level of information that would be most relevant for infrastructure-scale projects. One option is to modify Cal-Adapt to answer engineers' and architects' information needs.

Critical to the development and updating of any tool, however, is ensuring that tools meet the needs of end-users. To achieve this goal:

- Tools must be co-designed with the intended end user;
- There must be direct support and step-by-step guidance for using the tool appropriately; and
- The tools must effectively integrate social equity.

Existing tools could be modified and/or expanded to incorporate the level of information that would be most relevant for infrastructure-scale projects.

Summary: Platform, Tools and Data to Support the Climate-Safe Path for All

As described above, with important State policies in place, the tremendous breadth of research that has been funded through the state's climate assessments, as well as the conferences, platforms and tools already available or under development, key elements of an innovative and effective data and analytics system to support the building of climate-safe infrastructure are already in place and now must be tied together and augmented, not reinvented or replaced. Recommendation 3 intends to help the State put the pieces together.

Whether it is through a national scale connection to the Sustained Climate Assessment, or through augmentation of the state's adaptation clearinghouse, including its Technical Advisory Group, or the better use of gatherings such as the CAF, formalized processes should be developed in which state engineers and architects have deliberate and sustained interaction with physical and social climate change scientists from diverse research institutions, as well as professional organizations and other experts and stakeholders (see, for example, Chapter 8 for the engagement of financial experts).

Recommendation 3

Because of the diversity of State agencies, types of infrastructure and their vulnerabilities, and the specific needs for climate science, there cannot be a one-size-fits-all recipe for State agencies to engage with the climate change science community. That said, the State budget should provide full funding to State infrastructure agencies so they can dedicate time and support to their engineers and architects to substantively and collaboratively interact with climate scientists and other relevant experts in the creation of useful advice, guidance and tools on a regular and ongoing basis, in a way and at a level appropriate to their needs.

There are a number of steps the State can take in operationalizing this recommendation, including:

1. Expand timely options for state engineers and architects to travel outside of California to participate in professional conferences. The knowledge and talent to address the complex issue of global climate change often lies beyond the borders of California.
2. Develop a prioritized and expedited process for State agencies to leverage the expertise at universities and other research institutions in order to engage climate scientists on specific projects and studies.
3. Building on emerging efforts, Cal-Adapt should become more useful to sectors beyond the energy sector. Through an engaged, user-needs driven and broadly inclusive process, Cal-Adapt – and sister tools – could be updated to provide California-specific physical and social science information at the scale and resolution needed by state engineers and architects. Concerted outreach will be needed to raise awareness of this information among state engineers and architects. In addition, common data portals used by engineers should create links to Cal-Adapt to further raise awareness of available data in those places that engineers and architects already frequent.
4. In addition, relevant international and national science products and data sets should be more easily accessible (i.e., linked to) through Cal-Adapt to bring them to the attention of California data users.
5. All state geophysical research results should be consolidated into a single location (e.g., the State Open Data Portal and mechanisms should be created to regularly update these geophysical data (see Glossary). This would entail developing active data integration and consolidation policies and procedures to ensure users have access to all the state's best thinking on our changing geophysical environment. This should begin with linking all state-generated data sets and providing a common library to access and manage data. In the future, open data, data sharing and data quality policies should be developed that brings scientists' research results into the common platform, thus making continuously-updated information available to users.
6. Equally important to the quality of the data served up on Cal-Adapt, once the tool is established, tool developers (within academia, consultancies, or State agencies) should provide training to end users to help them become familiar with and supportive of innovation and best practices related to sustainability and resilience, including support for collaborative processes. This will be essential to its success and use by the engineering and architectural community.