Adapting Vermont's Transportation Infrastructure to the Future Impacts of Climate Change

VTrans Climate Change Adaptation White Paper

"Resilience science is based on the simple premise that change is inevitable and that attempts to resist or control it in any strict sense are doomed to failure." (Rees, 2010)

Vermont Agency of Transportation

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Cover-Photo:
Post-Irene damage along Route 100,

Courtesy of Lars Gange & Mansfield Heliflight

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Executive Summary

The purpose of this white paper is to provide an overview of climate related adaptation and resilience oriented efforts underway at the Vermont Agency of Transportation (VTrans). In recognition of the potentially negative consequences of climate change to well-being of Vermont, VTrans is in process of incorporating adaptive management, policies, and plans into every level of planning, design, operations, and maintenance.

Experts believe that global climate change will fuel increasingly frequent and severe weather events resulting in more frequent flooding in the Northeastern U.S. Existing flood vulnerability of the transportation system will be exacerbated by the effects of climate change increasing the risk of costly delays, detours, and premature infrastructure replacement. Recent flooding events following tropical storm Irene revealed the need for preemptive actions and planning to minimize the costs of similar events in the future.

Many of the lessons learned during the aftermath of Tropical Storm Irene are applicable to this effort. Enhancement of emergency procedures and systems, employee training, public outreach, and rapid hydraulic assessment tools are examples of some of the positive adaptive outcomes. Going forward, the Agency should expand programs and projects focused on gathering and monitoring data, increasing adaptive capacity, and incorporating risk-management into the decision-making process.

The recommendations made in this report have 'no-regrets' in that they will increase the effectiveness of long-term decision making under any future climate scenario. Due to the uncertainties associated with long-term climate forecasts, it is not prudent to significantly change specific management practices, codes, and standards, and other policies based on these forecast. Rather, the Agency should focus on minimizing vulnerability to current weather norms while developing holistic analytical tools to enable planners, designers, and decision-makers to better adapt to future climate conditions.

Introduction:

Making the case for climate change adaptation through responsible policies, planning, and development

The transportation system provides critical services to our communities. The network of roads, bridges, and rail lines enables a healthy economy, contributes to Vermonter's quality of life and provides emergency responders vital routes of access to impacted communities. By its very nature, transportation infrastructure is a public investment including many large-scale projects requiring large upfront investment. Preserving this investment from preventable failure is a primary responsibility of the Vermont Agency of Transportation (VTrans).

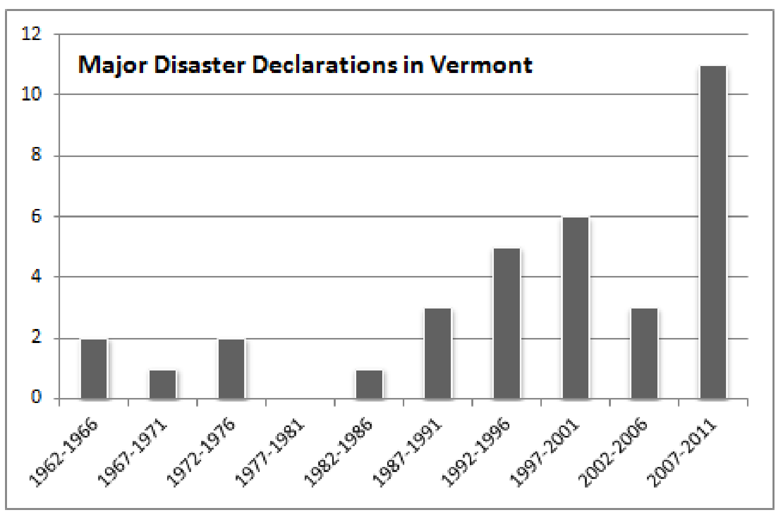

Figure 1: Number of FEMA major disaster declarations in Vermont in 5 year increments. The upward trend is attributable to an increase in storm frequency and continuing development in vulnerable areas. (FEMA, 2012) [1]

Preservation of transportation infrastructure imposes a significant fiscal constraint on the

[1] FEMA declares a Major Disaster when combined local, county and state resources are insufficient and the situation is beyond their recovery capabilities.

state. Recent events revealed the high levels of vulnerability of existing infrastructure. During 2011, two periods of flooding caused upwards of $260 million in damages to infrastructure in addition to severe economic and social disruption. Although these events exceeded the historical 100-year flood benchmark, climatologists predict increasingly frequent storm events. These projections suggest shifting vulnerability and risk to both the preexisting and planned built environment.

Communities and state agencies are now in the process of reevaluating their risk exposure and taking steps to minimize future damages by similar events. VTrans will serve a critical role in this process as a community advisor and regional leader in climate change adaptation planning and policy. The agency needs robust and flexible adaptation strategies in order to efficiently manage high consequence impacts of climate change.

Both recent trends and long-term climate models emphasize the importance of incorporating adaptive behaviors and standards into the transportation sector. In consideration of changing weather norms, it is imperative to build institutional adaptive capacity and incorporate adaptive best practices into the day-to-day duties and operations of the agency. Integrating these efforts into the agency's core values will allow for cost-effective solutions to a wide range of future climate related issues. The upward trend of major disaster declarations (Figure 1) and growing evidence of the local effects of climate change necessitates action on this issue.

The focus of this paper is on *adaptation* to rapidly occurring climate change rather than *mitigation* of greenhouse gas emissions to avoid worsening effects. Adaptation is the notion that society will need to adapt to climate changes that will occur, regardless of our success at reducing or mitigating the growth in greenhouse-gases. The development of a comprehensive adaptation plan is imperative to maintain communal viability while mitigating the potential economic, environmental, and social costs caused by intense storm events.

Climate Change in Vermont – Effects and Impacts

Scientific consensus is that global warming is occurring. Global average surface temperature has been and will continue to rise at an unprecedented rate. Due to the long lifecycle of carbon in the atmosphere, warming can be expected to continue for the foreseeable future. Atmospheric-oceanic general circulation models, moving thirty-year annual temperature averages, and recession of glacial and arctic ice-shelves support this conclusion.(IPCC-AR4) Although these trends vary regionally, scientific analyses of biophysical climate indicators reveal some of the effects of climate change occurring in Vermont.

Several studies show considerable changes in Vermont's climate currently taking place. Data from 1970 to 2000 confirms that the Northeastern United States is warming at a rate of nearly 0.5° F per decade. Winter temperatures have risen at a higher rate of 1.3° F per decade. (Frumhoff et al.) The increase in temperature is strongly correlated to a variety of environmental signals in Vermont:

- *earlier ice-out of lakes and waterbodies*
- *earlier bloom/budding dates;*
- *shifting seasonal transitions (a later fall/winter transition and an earlier winter/spring transition);*
- *increasing number of days above 90° F per year;*
- *decreasing seasonal snow depths;*
- *increasing length of the growing season;* and
- *advances in high spring streamflow;* (Betts; Hayhoe et al.)

These changes within the biophysical systems in the Northeast U.S. are in strong agreement with global predictions of low-resolution climate forecasting models. Furthermore, historical norms no longer apply as future predictors of climatic or meteorological events. (Betts; Wake)

The changing climate will result in other impacts, including an increase of seasonal temperature variation, duration of rainy/drought periods, and more frequent and severe extreme storm events. Table 1 describes the specific impacts of these changes on the transportation system. In addition, there will likely be unknowable and unforeseeable effects given the complex interconnected nature of climate, meteorological, ecological, and physical systems.

A thorough understanding of the effects and corresponding impacts of climate change forecasts is imperative to sustainable and responsible adaption. Because of Vermont's historical vulnerability to flooding, this paper is primarily focuses on the impacts caused by changing precipitation rates. A broad overview of the general climatic/meteorological changes and subsequent impacts on the transportation sector can be found in AASHTO's *Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges Background Paper*(AASHTO).

Climate/Weather Change		Impact to Infrastructure	Impact to Operations & Maintenance
Temperature	Increased extreme maximum temperature	- Premature deterioration of infrastructure; - Damage to paved roads from rutting, buckling, and raveling; - Bridges stressed by thermal expansion and movement;	- Safety concerns for highway workers limiting activities and work time; - Increased costs of bridge inspection and repair; - Need for more stringent weight restrictions;
	Greater variability and range of maximum and minimum temperatures,	- Increased frequency of freeze-thaw events leading to potholes and heaves; - The increase in freeze thaw cycles will damage bridge expansion joints.	- Longer road-construction season; - Increased load restrictions due to an increase in the duration of the thaw aka 'mud-season' - Increased use of roadsalt due to water freezing on the road.
Precipitation	Greater seasonal precipitation variation	- More rain in the winter coupled with freeze-thaw cycles increases the risk of landslides, slope failures, and run-off caused floods; - Increased soil moisture levels may lead to loss of structural foundation integrity of roads, bridges, and tunnels; - Bridges and signage at risk from freezing-rain aka ice-storms	- Increased likelihood of freezing rain events causing more traffic disruptions, accidents, and delays; - Fewer days with snow and ice on roadways; - Risk of inundation flooding around reservoirs and lakes (specifically, Lake Champlain) - Increased likelihood of landslides.
	Increased intense precipitation and storm events	- Greatly increased risk of fluvial erosion embankment deterioration; - Increased rate of bridge scour or aggregation; - Greater likelihood of exceeding culvert capacity; - Signs and bridges stressed by increased wind;	- Greater road closures due to washout and flooding; - Construction sites may face severe erosion prompting delays; - Increased weather related accidents; - Increased lane obstructions due to drifting of snow, flood, or tree/cable downfall; - Electrical disturbances could lead to loss of signaling, delay maintenance activity, and pose risk to personnel - Increased need for debris removal from bridge openings.
Coastal Storms (Hurricanes, Tropical Storms)	Increased intensity, impacts ranging further inland	-See impacts above	- Increased frequency of storm warnings and precautionary measures

Table 1: Anticipated effects and impacts of climate change on the transportation sector in Vermont (AASHTO)

The multifaceted and complex nature of the impacts on the transportation sector will require resource prioritization. Due to uncertainties associated with both the magnitude and timing of climate change effects, it is important to implement policies and plans addressing both current and anticipated vulnerabilities. Rising temperatures, larger temperature and precipitation swings, and the increasing frequency of severe storm events may have significant impacts on long term funding and day to day operation of Vermont's transportation network. Although there are many real problems associated with rising temperatures and shifting seasonal transitions outlined in Table 1, vulnerability to flooding remains the most pressing problem that must be addressed.

Recent Flood Events:

In 2011, Vermont experienced two destructive periods of flooding surpassing historic records. These events differed in type (inundation vs. flash), cause (snowmelt coupled with record seasonal rainfall vs. tropical storm precipitation on inundated soils), and magnitude of damage ($8 million vs. $250 million). These events were particularly striking because of their temporal proximity and the magnitude by which high-water marks and damages exceeded previous records.

Substantial snowmelt, in addition to record-breaking spring rainfall, elevated Lake Champlain to 3.3 feet above flood stage and a full foot past the previous high-water mark set in 1892. Three major rivers experienced 100-year flood events. Lake Champlain exceeded flood levels for two months and increased in area by 15% (The Adirondack Almanack) causing destructive shoreline erosion and flooding. Debris and landslides blocked shipping lanes, water levels inundated ferry docks, and wave erosion damaged several roadways.(Nearing) The flooding resulted in $6 million damage to transportation infrastructure in Vermont with additional damage done in New York and Quebec.(Sherman)

Just three months later, Vermont experienced catastrophic flash flooding associated with Tropical Storm Irene that resulted in significant damage to transportation infrastructure causing fluvial erosion which destroyed road and railbeds, undermined bridge foundations and washed out culverts. Box 1 displays the magnitude of the damage caused by the event. The total cost of infrastructure damage was in the range of $250 - 300 million.(Gram) Electrical, water, and communication systems also sustained severe damage or destruction. Road damage completely isolated 13 communities in the southern and central regions compounding the work of emergency responders.

These events revealed high levels of vulnerability to flood hazards within the transportation sector. In both cases, federal assistance was required when local and state resources proved insufficient to address the full extent of the damage.

Irene Transportation Damage

- State highway system: >500 miles of road and ~200 bridges damaged; costs to rebuild: $175 million- 250 million (lowered from initial estimates of $620 million)
- Municipal Roads: Estimated >2000 road segments damaged, >280 bridges and ~960 culverts damaged
- Railroad: >200 miles of rail and 6 bridges in the state-owned rail system damaged, costing the state an estimated $21.5 million. New England Central Railroad also reported damage to private railways, with repairs required at 66 locations.
- Bus: Green Mountain Transit Authority offices in Berlin sustained flood damages, including 13 vehicles.

Box 1 (Pealer)

Climate Change and State Leadership

Vermont has a strong history of environmental conservation and preservation of the state's natural resources. In recognition of the threats posed by climate change, the state's leadership has moved to cut greenhouse gas emissions and investigate the consequences of climate change.

The *Governor's Commission on Climate Change* (Executive Order #07-05) was formed in 2005 from a wide range of state Agencies and stakeholders. In 2007, the Commission issued a comprehensive report outlining 38 policy and project recommendations. The report included the recommendation for a council or other mechanism to address climate change adaptation in Vermont. The report suggests using a cross-functional approach to integrate public, private, and academic resources to better educate the public, disseminate best-practices, and investigate mitigation strategies.

In 2010, the University of Vermont and State of Vermont Climate Collaborative - one of the outcomes of the Governor's Commission report – asked various state agencies, to prepare brief white papers indentifying ongoing activities and projects, informational or data gaps, and any known strategies to address potential impacts of climate change. Agencies are now in the process of further compiling and refining these White Papers to provide a foundation for future climate change oriented programs and policies.

In 2011 Governor Shumlin formed the *Vermont Climate Cabinet*. The Cabinet, chaired by the Secretary of Natural Resources, is a multidisciplinary approach to enhance collaboration between various state Agencies. Its primary objectives include providing the Governor with advisory information and facilitating climate change policy adoption and implementation.

Primary Goal and Objectives

The primary goal of a VTrans climate change adaptation policy is to minimize long-term societal and economic costs stemming from climate change impacts on transportation infrastructure. This goal is in line with VTrans' mission, vision, and values:

EXCELLENCE & INNOVATION: Cultivate and continually pursue excellence and innovation in planning, project development, and customer service.

- Ensure that there are viable alternative routes around vulnerable infrastructure such as bridges and roadways;

SAFETY: Make safety a critical component in the development, implementation, operation and maintenance of the transportation system.

- Develop contingency plans for a wide-variety of climate impacts to be implemented as data/information becomes available;
- Utilize information technology to inform stakeholders during times of emergency;
- Educate of the public and other stakeholders on the threats posed by climate change and fluvial erosion hazards;
- Increase inspection of infrastructure if warranted by climate change indicators;

PLANNING: Optimize the movement of people and goods through corridor management, environmental stewardship, balanced modal alternatives, and sustainable financing.

- Apply a decision-making framework to incorporate cost-benefit analyses into adaptive plans and policy;
- Increase adaptive capacity among stakeholders so that adaptive planning can be quickly implemented upon realization of risk;

ENVIRONMENTAL STEWARDSHIP: Build, operate and manage transportation assets in an environmentally responsible manner.

- Work to protect essential ecosystem functions that mitigate the risks associated with climate change;
- Educate individuals within the agency to use best-practices during recovery periods to avoid ecological damage that may further exacerbate risk;
- Recognize the interconnected nature of our built environment with ecological processes.

PRESERVATION: Protect the state's investment in its transportation system.

To achieve this goal, policies must overcome short-term budgetary, social, and institutional constraints to avoid potentially untenable future costs.

Constraints on Climate Change Adaptation

Limited **budgetary** resources present the greatest challenge to mid- and long-term resilience investments. Vermont, like many other rural states, struggles to maintain existing system functions due to limited financial resources. Traditional sources of transportation revenues at both the federal and state levels are in decline, and the current formula associated with the national Highway Trust Fund distributions could be adjusted in a way that would be disadvantageous to Vermont. Given the current fiscal climate, an adaption-specific investment program would not be feasible. Instead, adaptation efforts and best practices should be incorporated during traditional system reinvestments, such as rehabilitation and maintenance. This approach is in use in Massachusetts to minimize the potentially large upfront financial burdens associated with adaptation.

Regulatory hurdles add complexity to disaster response and recovery funding. Due to the budgetary limitations outlined above, federal disaster relief funding represents a critical avenue for rebuilding a more resilient transportation network.

There are two federal programs responsible for response and recovery funding aid. The Federal Highway Administration (FHWA) distributes funds for use on federal aid highways such as those under state jurisdiction and major town highways. The Federal Emergency Management Agency's (FEMA) public assistance program gives aid for all other town highway, bridge, and culvert projects. Each program has specific requirements for project eligibility. Due to the limited capacity in many of the small communities impacted by Irene, VTrans has played an integral role negotiating the complex and stringently upheld federal code and regulation.

FEMA standards limit recovery funding to projects based on current state transportation codes and standards. This limitation inhibits the state from upgrading damaged structures beyond the state codes and standards which proved to be inadequate during Irene. Upgrading the town codes and standards is underway to alleviate any future ambiguity in funding eligibility. These standards must implement adaptation oriented design and maintenance considerations while minimizing the regulatory burden placed on towns. This is especially problematic in Vermont where it is prohibitively expensive to use a one-size-fits-all approach to culvert, bridge, and drainage design with no regard of risk prioritization.

The National Flood Insurance Program (NFIP) requires property owners with structures located in 100-year floodplains to purchase flood insurance. This requirement has been shown to result in significant long-term savings; however, its effectiveness is entirely dependent on the spatial and temporal resolution of Vermont's floodplain maps. Historically in Vermont, two-thirds of flood damage occurs outside of mapped flood areas.(Medlock) The flood maps identify areas at risk of inundation type flooding rather than the fluvial erosion hazards seen during Irene-like events. Areas with outdated maps may be inadvertently leaving themselves open to potentially high levels of unreasonably adverse risk. Nine of fourteen counties have not updated their flood hazard maps in over twenty years.(VT DEC Watershed Management Division)

The **scientific** uncertainties associated with climate change forecasting at the regional scale inhibits engineers from easily incorporating adaptation into the design process. Vermont currently extrapolates infrastructure design specifications using historic data analyzed in the *Cornell Atlas of Precipitation Extremes for the Northeastern United States and Southeastern Canada*. This resource may not reflect actual meteorological conditions as it does not include data taken after 1960. Due to the unprecedented magnitude of forecasted climate change, there is consensus among climatology and adaption experts that historic trends will prove inadequate as a predictive model for the future.(Hyman, Lupes and Perlman)

Economic and **political** changes continue to be a concern for long-term implementation of adaptation policies imposed over a length of time significantly greater than that of economic and political cycles. Budgetary constraints necessitate a long-term approach to avoid large and unaffordable upfront costs but leave these plans susceptible to changes in leadership. Although the political and economic conditions in Vermont have been relatively stable, predicting future conditions is nearly impossible. Overcoming this barrier will require motivated and educated elected officials and a populace that understands the need for investments in adaptation necessary in the long-term.

Ongoing projects within VTrans

VTrans is collaborating with several other agencies to implement various adaptation and resilience oriented projects. Work is already underway to improve emergency response, inventory state assets, and educate/train various stakeholders to better manage flood risks. The devastating flooding of 2011 prompted a reevaluation of state policies concerning proper management of flood risks at the local, regional, and state level. These efforts are key actions to reduce existing flood vulnerability. These programs and initiatives, some of which are described below, lay the foundation for further development of adaptation tools and policies as priorities evolve over time.

LiDAR (Light Detection And Ranging) Mapping

VTrans, RPCs and some municipalities are undertaking LiDAR mapping efforts along primary transportation and river corridors. LiDAR provides detailed topographic data accurate within ~ 0.5m (1.5ft) to increase the precision of computerized flood models, update FEMA's 100-year floodplain maps, and support the use of risk assessment tools.(Csanyi) These programs should be expanded to include vulnerable transportation corridors to improve hydraulic models.

In the past, VTrans has collaborated with the Agency of Natural Resources (ANR) and the Lake Champlain Basin Program to fund mapping efforts around Lake Champlain to better predict the potential impacts of inundation type flooding.[2] The mapping effort is progressing at a rate of approximately one county per year. There are funding agreements in place to map several more counties; however, long-term funding agreements to cover the whole state have not been reached.

State asset management

The state asset inventory and management system provides valuable feedback on best management practices, efficient resource allocation, and sustainable transportation funding. The state is in the process of collecting condition and performance data on state-owned small and large culverts, bridges, and pavement. This project recently finished collection along the interstate system. This data includes a wide range of environmental, traffic volume, and structural factors and is used to inform project prioritization and funding decisions. VTrans is working towards development of more sophisticated deterioration models that will allow the agency to more effectively plan for long-term funding needs and to quantify performance trade-offs under different scenarios.

Climate changes will require frequent updates of environmental factors in these models. For example, pavement deterioration curves are partially dependent on frost depth, bridge refurbishment rates depend on the frequency of significant thermal expansion, and culvert longevity depends on the frequency of flood events exceeding their engineered upper limit. For this reason, it will be important to increase the frequency at which these data sets are updated and reassess the models on a regular basis to ensure that variables are properly weighted.

Another important avenue for climate change adaptation is creation of state asset inventory. Currently, there is a plethora of data available in various inventory systems run by RPCs, VTRans, ANR and the Vermont Center for

[2] This is particularly important in states with vulnerable coastlines exposed to sea level rise: In 2009, the LiDAR in the Northeast project began collecting measurements for the coastline of New England. In 2010, New York City took LiDAR measurements of its entire cityscape as part of PlaNYC, Mayor Bloomberg's broad environmental agenda. Washington and Alaska have extensively mapped their coastline and advocate using a site specific approach in conjunction with LiDAR data.

Geographic Information (VCGI). Standardization of the data in each of these areas will allow for the creation of more robust and holistic tools.

Flood resilience training programs

The Flood Resiliency Training Programs aims to educate key audiences on best management practices, river dynamics and geomorphology, and potential impacts of floods on infrastructure. Participants include VTrans personnel such as heavy equipment operators, field supervisors, and design engineers; Tri-State (ME, VT, and NH) partners; contractors; and consultants. The curriculum will be tailored to the expertise and daily activities of each group. This program will increase the adaptive capacity of the Agency and allow for responsible reactions to natural disaster events in the future.

Transportation Resilience Plan

VTrans will be developing methods and tools to identify roads, bridges and other transportation infrastructure that are vulnerable to flooding and fluvial erosion, quantify risk as a means to prioritize needs, and evaluate strategies to mitigate risk. The purpose is to proactively identify transportation facilities that have a high risk of failing due to flooding so mitigation strategies can be implemented using available project development and funding mechanisms prior to the next disaster. These transportation resiliency plans will be developed on a watershed basis and will involve the integration of river corridor and transportation corridor planning. The plan will create a methodology to ascribe quantitative measure of risk. incorporating flood vulnerability assessment[3] and a host of other factors such as alternative routes, historic repeat damage, and economic or social importance. This process will allow for efficient adaptation prioritization of the state's vulnerable infrastructure. Methods will be applied within one or more watersheds before expansion of the program statewide.

Rapid culvert sizing

In response to tropical storm Irene, VTrans quickly developed a computerized process to rapidly assess culvert specifications using a variety of site-specific and hydrological data sources. This tool cut the time to determine proper culvert specifications from 15-20 hours to 2-3. This tool allows VTrans to expedite support during emergencies, and reassess the vulnerability of culverts as precipitation models with higher certainty become available.

Resilient Vermont Project: Stronger Communities, Ecosystems, and Economies

VTrans and a wide variety of stakeholders are working with the Institute for Sustainable Communities to bolster the state's resilience to extreme weather events. This will be achieved by compiling an inventory or map of resilience building activities already underway, creating a shared definition of 'resilience' specific to Vermont, and allowing for prioritization a variety of actions and investments to increase resilience. The underlying role of the transportation network to the state's livelihood necessitates a collaborative role in the project.

Potential Actions

Adaption oriented policies and projects will allow the agency to make more informed plans and decisions. Standardization and compilation of data will allow for the creation of invaluable trend-revealing tools. These tools can be combined with a timeframe to update the Agency's policies and documentation as new scientific theories, data, and technologies become available. This will allow the Agency to quickly incorporate best management practices, and reassess the costs and benefits of an adaptation oriented program. A reevaluation process based on continuous improvement through data analysis is a critical component of building adaptive capacity.

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[3] Flood vulnerability based on fluvial erosion hazards determined by ANR's geomorphic assessment tools and historic river dynamics

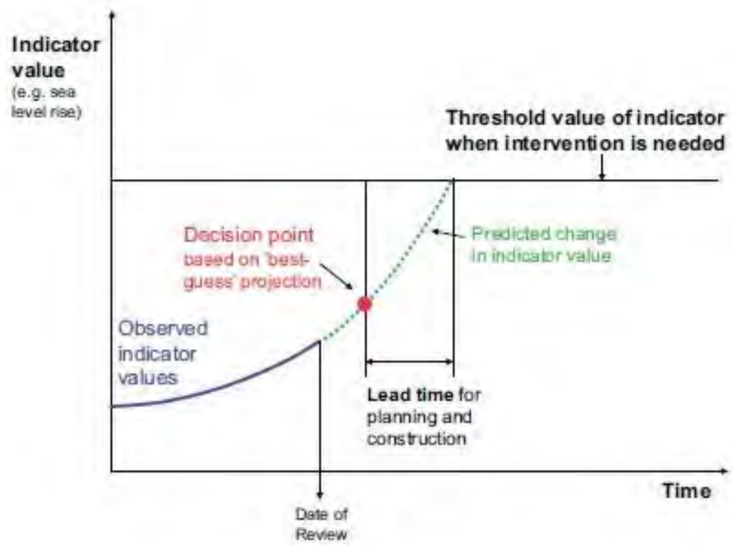

Figure 2: Schematic diagram of the thresholds, lead time, and decision points used in the Thames Estuary TE2100 project

Data gathering, monitoring, and standardization

Improve and standardize infrastructure damage record keeping

An electronic database of compiled and standardized *Project Worksheets* (PWs) and *Detailed Damage Inspection Reports* (DDIRs) would be an invaluable analytic tool to identify vulnerable infrastructure with repeat damage or insufficient design standards. The PW is used by FEMA to define the scope of work and cost estimate for a project. It is the basis for funding under the FEMA Public Assistance Program. DDIRs is an equivalent documentation used by FHWA to document scope of work and cost estimates Current regulation requires towns and the state to retain these documents for only three years, leaving historical data nonexistent or incomplete.

Coupling this database with an electronic submittal system would automate data entry, continue the evolution from paper to digital recordkeeping, and warn users if fields are not entered correctly or are incomplete. In the event of a disaster, such a system would speed the federal funding process to ensure that recovery work is completed in the 180 day federal funding eligibility window. Iowa DOT's Information Technology Division developed a similar in-house electronic submittal system which proved to be a great success following flooding events in 2011. (Inside Newsletter, Feb. 2012)

Critical climate threshold monitoring

Research should be undertaken to identify climate related thresholds that may lead to a significant increase in infrastructure deterioration; for example, temperature thresholds for pavement degradation will signal appropriate decision points to implement higher standards for new projects or reassessment of vulnerable infrastructure. The creation of thresholds allows for efficient allocation of resources given the wide range of possible climate scenarios. Potential thresholds include:

- The frequency of freeze-thaw events at which point pavement deterioration becomes unacceptable
- An increase in the frequency of severe storms would prompt increased inspections of vulnerable roadways, culverts, and bridges.
- Changes to the ten rolling ten-year average of q25 (4% chance) flood values may prompt reanalysis of the hydraulics standards used to set town road and bridge standards for FEMA eligibility and infrastructure design specifications.
- The failure rate of certain structure designs exceeding predetermined levels due to climatic factors may prompt a shift to new infrastructure designs or types.

The use of thresholds is particularly valuable in the case of flooding because of the large uncertainties inherent in future forecasts of precipitation data. Thresholds allow policy makers to avoid costly over-adaptation while maintaining contingency plans for possible climate scenarios.

Expand the State Asset Inventory

Expanding the quality and quantity of data in the state's asset inventory will allow VTrans to better track existing infrastructure and identify weak links in the network so changes can be made before they fail. The state should continue to add small culverts in the state asset inventory program. Irene revealed culverts as a common weak link in the transportation network.

Develop and apply deterioration models for bridges, pavements and other assets as appropriate. These models would allow VTrans to evaluate the tradeoffs associated with different funding scenarios. For example, the agency may want to evaluate the tradeoffs related to diverting funding from its paving program to address several bridges that are vulnerable to flooding. The model would show the resulting deterioration in pavement condition and the cost of deferred maintenance to help inform the decision: does the risk to flooding justify the diversion of funds?

Support Local Asset Inventories

Currently, the state provides several financial incentives to encourage towns to compile inventories of roads, bridges, causeways, culverts, and any highway-related retaining walls on Class 1, 2, and 3 town highways. VTrans developed the Vermont On-line Bridge and Culvert Inventory Tool (VOBCIT) to assist municipalities with the inventories of town highway bridges and culverts. VOBCIT has been in use for several years and VTrans is undertaking a review to improve its functionality and integration with GIS. Another critical improvement will enhance VOBCIT's ability to integrate culvert and bridge geomorphic compatibly screening prepared as part of river corridor plans. Integrating the standard culvert and bridge condition assessment with geomorphic compatibility will help municipalities adapt to climate change by prioritizing infrastructure needs in their capital programs. In addition, information should be collected on exempt infrastructure such as closed drainage systems and class 4 roadways.

Creation of analytical tools

While data is collected, analytical vulnerability and risk assessment tools should be developed alongside data collection and improvement. As climate change effects, impacts, and models increase in certainty, the output from the tools will become more effective. Many of these tools can be used with existing knowledge and have benefits in any climate scenario:

- Enable faster responses to flooding through a real-time monitoring system to warn communities and the agency if 6 or 24 hr precipitation data exceeds the design specifications regarding maximum flood levels.
- Allow for more thorough identification of vulnerabilities through GIS based compilation of meteorological data, precipitation model forecasts, high-resolution topographical mapping, and state assets.
- Continue enhancing the *Rapid Bridge Program* with tools to easily compare the differing costs of the infrastructure given specifications determined by possible climate scenarios.

Update project prioritization guidelines

VTrans uses a technical prioritization system to guide decisions about capital programming for roadway and bridge rehabilitation and reconstruction projects that use state and federal funds. The scoring methodology varies somewhat for bridges and roads but both are generally based on structural condition, consistency with design standards, safety, importance to the statewide road network, cost, and regional priority. VTrans prioritizes many other types of transportation projects (transit and aviation for example), but existing road segments and bridges are particularly vulnerable to flooding and fluvial erosion and, if not designed adequately, could fail and/or severely impact nearby public infrastructure and private property.

VTrans should modify the roadway and bridge prioritization system to account for a facility's vulnerability and risk to and impact on flooding and fluvial erosion. This change would elevate vulnerable facilities in the project development process and in the long run would improve overall system resiliency.

Implement the VTrans Irene Innovations Task Force recommendations

The *Irene Innovations Task Force* was formed to identify innovative practices or ideas resulting from lessons learned during the tropical storm Irene response and recovery effort. Many of the recommendations of the task force are directly relevant to critical climate change adaptation practices. These include fostering greater adaptive capacity, analytical tools, and emergency-response best practices.

Revise the Hydraulics manual

Update the current hydraulics manual and review it on a reoccuring[4] basis to incorporate new or improved best practices. Rapid changes in precipitation, channel and watershed characteristics, land development, may require different assessment techniques to ensure maintenance of tolerable levels of risk. New information sources, precipitation models, and analytical techniques may reveal potential gains in the effectiveness and efficiency of the infrastructure development and planning.

[4] The manual should be reviewed at predetermined times: prompted by environmental indicators or design specifications crossing thresholds or on a regular interval while the agency gathers new data and develops best management practices.

Increasing adaptive capacity

Adaptive capacity is a broad term for the ability of an organization or society to change design, function or behavior in response to or anticipation of external events or changing conditions. Organizations with adaptive capacity consciously interact with their environments which, in turn, provide information-rich feedback, stimulate learning, and ultimately prompt improved performance.(Sussman) There are four general behaviors essential to fostering adaptive capacity within organizations: external focus, network connectedness,

Factors	Examples
Economic resources	Wealth of individuals and localities.
Technology	Localized climate and impact modeling to predict climate change and variability; efficient irrigation systems to reduce water demand.
Information/awareness	Species, sector, and geographic-based climate research; population education and awareness programs.
Skills/human resources	Training and skill development in sectors and populations; knowledge-sharing tools and support.
Natural resources	Abundant levels of varied and resilient natural resources that can recover from climate change impacts; healthy and inter-connected ecosystems that support migration patterns, species development and sustainability.
Infrastructure	Systems that provide sufficient protection and enable efficient response (e.g., wireless communication, health systems, air-conditioned shelter).
Institutional support/governance	Governmental and non-governmental policies and resources to support climate change adaptation measures locally and nationally.

Figure 3: Key factors for adaptive capacity (Pew Center on Global Climate Change , 2009)

inquisitiveness, and finally, innovation. When applied to climate change issues, Figure 3 displays the primary attributes that are used as adaptive capacity metrics. Focusing on the following behaviors is essential to further increasing capacity with the agency.

External Focus

External focus is the development of relationships with outside experts and peers; the ability and willingness to incorporate new ideas and information into plans, policies and frameworks; and the constant evaluation of the positive and negative effects of implemented programs.

As climate change garners increased attention from the scientific, political, and business communities, information and data must continue to be updated and further refined. VTrans should review and integrate relevant best practices and downscaled climate information as it becomes available. There are several web based tools compiling and tagging adaptation related research to aid in filtering relevant information.[5] VTrans and other Agencies should contribute and utilize these resources.

Network Connectedness

Efficient climate change adaptation requires a multi-disciplinary and multi-agency approach. Adoption of common goals and objectives between the various state agencies would assist in cross-agency collaboration and

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[5] The Climate Adaptation Knowledge Exchange (http://www.CAKEx.org) is aimed at "building a shared knowledge base for managing natural systems in the face of rapid climate change." WeADAPT.org (http://www.weadapt.org) is a similar tool "designed to facilitate learning, exchange, collaboration and knowledge integration to build a professional community of practice on adaptation issues while developing policy-relevant tools and guidance for adaptation planning and decision-making."

communication. The interlinked nature of the state's transportation infrastructure with economic and environmental policy requires cooperation among a multitude of stakeholders. Furthermore, such an action would emphasize the importance of considering possible climate change related problems and solutions in relation to the State's primary tasks. The Climate Cabinet encourages this behavior through its collaborative approach to problem solving. (see *Climate Change and State Leadership* above)

Inquisitiveness

Inquisitiveness requires an organization that not only asks questions, but one that asks the right questions. This involves transforming information and data into knowledge to influence decision-making. Network connections greatly expand the ability of an organization to utilize expert knowledge to answer these difficult questions. The decision-making framework discussed below begins to delve into the appropriate questions for informed and adaptive policy creation. See Figure 4.

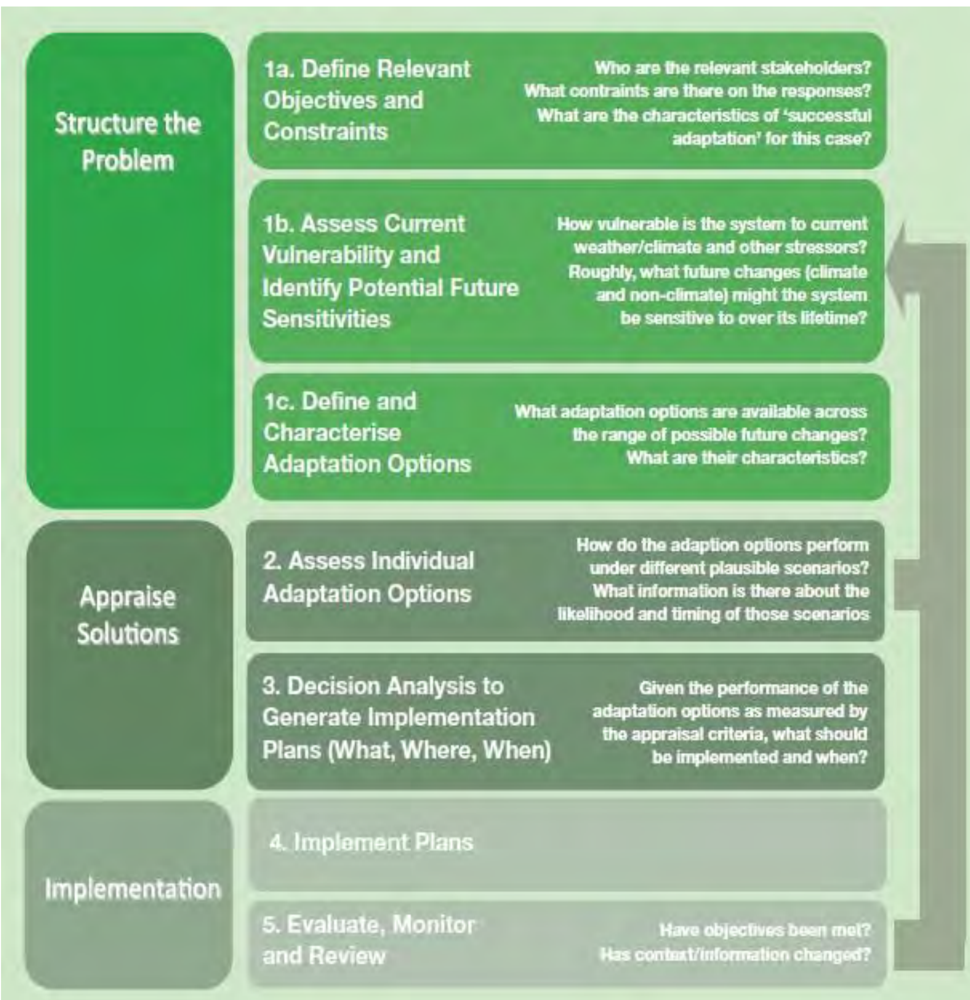


Figure 4: A generic decision making framework, (Ranger, Milner, Dietz, Frankhauser, Lopez, & Ruta, 2010)

Innovation

Innovation allows the adaptation process to move from a purely reactionary process to one of anticipatory action. Vermont's unique history, culture, and economic distribution will require unique solutions to climate change issues.

Applying a decision-making framework

Effective adaptation planning requires decision-making under great uncertainty. The traditional approach to adaptation planning has been 'science-first,' where the process begins with generation and interpretation of climate model scenarios, analysis of impacts, and finally, assessment of options to mitigate those impacts. (Reeder and Ranger) This approach is vulnerable to a 'ballooning of uncertainties'[6] making assessment of adaption options impractical. (Wilby and Dessai) Other inefficiencies arise if

[6] 'The the accuracy of climate predictions is limited by fundamental, irreducible uncertainty. Each step of extrapolation of economic impacts from local physical impacts from regional climate from global climate compounds inherent uncertainties. (Wilby and Dessai)

more information is needed to assess the various adaptation options. This forces decision makers to return to the beginning of the process to develop new models or gather new data. The opposite of the 'science-first' process has been proposed to limit these inefficiencies. This is known as a 'context-first'[7] approach.

The context first approach begins by structuring potential adaptation problems within relevant goals/objectives, current vulnerabilities and sensitivities, and adaption strategies or options. The adaptation planner can then get an idea of the nature of the adaptation needs, relevant options, and information gaps. By beginning with the problem, the approach encourages planners to think broadly about interactions with other risks and priorities and find strategies that have co-benefits with other policy areas.(Reeder and Ranger)

The Thames Estuary 2100 project (TE2100) is an example of a context-first approach applied to climate change adaptation problem. The project began by assessing the vulnerability of the flood protection system in London before outlining solutions to sea level rise and identifying threshold points at which the current or planned flood defense system would fail. This approach allowed planners to build flexibility into their long-term adaptation strategy. See *Appendix A: Application of a* Context-First *decision making process* for a step by step breakdown of the process applied to TE2100.

The questioning process displayed in Figure 4 should be integrated into the general planning process for new projects and high-risk infrastructure. It is not necessary for this approach to consume excessive valuable time. For example, the adaptation planner may use back-of-the-envelope analysis to determine adaptation needs, options, and information gaps. It is acceptable to discontinue the process if it is determined that the project has little vulnerability or sensitivity to climate change.

[7] This approach has many different names in literature including 'context-first,' 'bottom-up,' and 'access risk of policy.'

Appendix A: Definitions

Adaptation: The adjustment in natural or human systems to a new or changing environment caused by climate change.(IPCC-AR4)

Adaptive Capacity: the ability to design and implement effective adaptation strategies or to react to evolving hazards and stresses so as to reduce the likelihood of the occurrence and/or the magnitude of harmful outcomes resulting from climate-related hazards. (Brooks, Adger and Kelly)

Flexibility: An adaptation option's ability to be adjusted to new information or circumstances in the future. (Ranger, Millner, et al., 2010)

Mal-adaptation: Unnecessary costs which may arise from inaction (failure to adjust standards and practices to changing conditions), over-adaptation (adjustments made that are proven to be unnecessary given the climate realized), under-adaptation (where adjustments are not enough), or incorrect adaptation (adjustments are found to be ineffective or even counter-productive to minimizing costs of climate change). (Ranger, Millner, et al., 2010)

No-Regrets measures: adaptation measures that provide benefits under any climate scenario. These may include measures with significant cross-sector benefits, or those that provide benefits in managing the current weather and climate variability. This does not imply no-cost nor tradeoff investments.

Resilience: The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.(Roberts)

Robustness: An adaptation option's ability to perform adequately across a wide variety of possible futures. (Ranger, Millner, et al., 2010)

Sensitivity: The degree to which a system is affected, either adversely or beneficially, by climate related variables including means, extremes and variability

Uncertainty: An expression of the degree to which a quantity (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable.

Vulnerability: The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability of extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.(Roberts)

Appendix B: List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ANR	Agency of Natural Resources
DDIR	Detailed Damage Inspection Reports
DOT	Department of Transportation
FEMA	Federal Emergency Management Agency
IPCC-AR4	International Panel on Climate Change - Fourth Assessment Report
MPO	Municipal Planning Organization
NFIP	National Flood Insurance Program
PW	Project Worksheet
RPC	Regional Planning Commission

TE2100	the Thames Estuary Project 2100
TRP	Transportation Resilience Plan
VT DEC	Vermont Department of Environmental Conservation
VTrans	Vermont Agency of Transportation
LiDAR	Light Detection And Ranging

Appendix C: Resources and Tools

Knowledge Exchange Centers

The Climate Adaptation Knowledge Exchange (http://www.CAKEx.org) is aimed at "building a shared knowledge base for managing natural systems in the face of rapid climate change."

WeADAPT.org (http://www.weadapt.org) is a similar tool "designed to facilitate learning, exchange, collaboration and knowledge integration to build a professional community of practice on adaptation issues while developing policy-relevant tools and guidance for adaptation planning and decision-making."

Georgetown Climate Center Clearing House (http://www.georgetownclimate.org/adaptation/clearinghouse) "The Adaptation Clearinghouse seeks to assist state policymakers, resource managers, academics, and others who are working to help communities adapt to climate change." The clearinghouse provides a database of organizations and research searchable by impact, sector, and resource type.

Georgetown Climate Center – State and local plans (http://www.georgetownclimate.org/adaptation/state-and-local-plans) This is a compendium of the various state and local plans related to adaptation policy.

Nova Scotia Climate Change Clearinghouse (http://climatechange.gov.ns.ca/content/adaptation/) "This site was created to support individuals, organizations, and communities in their efforts to adapt to the impacts of climate change. While the province is taking aggressive action to cut greenhouse gas emissions that cause climate change (mitigation), this site is devoted to dealing with its growing impacts: changing temperature, sea level, rainfall, and extreme weather (adaptation). The Adaptation Clearinghouse is a shared public project – intended to evolve in response to your feedback and our collective efforts to manage change."

Guides & Tools

Tools for Estimating the Effects of Climate Change on Flood Flow (http://www.mfe.govt.nz/publications/climate/climate-change-effects-on-flood-flow/index.html) The main aim of this guidance manual is to help local authority staff – including river managers, engineering staff and asset managers – to manage and minimize the risks posed by increased flood risk due to climate change. More specifically, the manual provides good practice guidance for incorporating climate change impacts into flow estimation. It does this by providing:

- information on the key effects of climate change on flood risk
- methods for estimating changes in the frequency and/or magnitude of rainfall
- methods for converting changes in rainfall to changes in flow rate
- methods for converting changes in flow rate to changes in inundation
- some case studies to illustrate these methods.
- Issues for engineering design

CRiSTAL – Community Risk Screening Tool – Adaptation and Livelihood (http://www.iisd.org/cristaltool/) a screening tool designed to help project designers and managers integrate risk reduction and climate change adaptation into community-level projects. It helps project designers and managers:

- Understand the links between livelihoods and climate in their project areas
- Assess a project's impact on community-level adaptive capacity; and
- Make project adjustments to improve its impact on adaptive capacity and reduce the vulnerability of communities to climate change.

Climate Wizard (http://www.climatewizard.org/) a web-based analysis and mapping tool that uses state-of-the-art climate models and advanced statistical analysis to examine both the current and future climate conditions of any place on the Earth. Pre-calculated map products are available through a free webpage where users can easily visualize and download data for both historic and future climate conditions. Future climate projections are based on General Circulation Models output produced under three different greenhouse gas emission scenarios for two future time periods; mid and end century. Additionally the user has the ability to examine the statistical variations of 16 different general circulation models used to generate these future climate projections by displaying individual model results or selected model combinations.

UKCIP Adaptation Wizard (http://www.ukcip.org.uk/wizard/) The Wizard will take you through a 5-step process that will enable you to

- Teach yourself, your colleagues and wider professional network about climate change adaptation.
- Access the information, tools and resources UKCIP provides to help you deal with climate change.
- Conduct a high level assessment of your sensitivity to the current climate and to future climate change.
- Make a decision, or develop a project, programme, policy or strategy, that is resilient to climate change.
- Develop a climate change adaptation strategy in a way that internalises the learning process. The benefit of this approach is that the capacity of the individuals involved and of your organizational as a whole to respond to climate change will be enhanced. UKCIP (2010). [The UKCIP Adaptation Wizard v 3.0. UKCIP, Oxford]

Appendix D: Application of a Context-First *decision making process*

Reproduced from the *World Resources Report: Decision Making in a Changing Climate* (Reeder and Ranger)

To give an example of how a context-first approach can be applied, below are a series of steps carried out in the TE2100 project:

I) Structuring the problem:

1) Understand current vulnerability of the system. *For example, evaluating the current level of flood risk and the standards of protection around the Estuary*

2) Map future sensitivities to climate change and other risks. *For the Thames Estuary, science and modeling initially suggested a maximum potential increase in extreme water level of 2.7m in 2100. For sensitivity testing, an upper bound of 4.2m was used to represent a catastrophic sea level rise scenario. The upper bound was deliberately pessimistic to take account of most known wild cards.*

3) Assess known (or estimated) key thresholds in between now and this upper-bound figure in terms of vulnerability to impacts. *Key thresholds for sensitivity in the system include: (i) a limit of the present system of walls and embankments is reached;, (ii) the level of sea level rise at which the current Thames Barrier system as designed will fall below the target protection level (1 in 1000); (iii) the engineering limit of the Thames barrier with modifications; and (iv) the limit to adaptation, at 5m it would become difficult to continue to protect London in its current form, potentially requiring some retreat.*

4) Identify feasible adaptation response options (at high level) to cope with these thresholds. Identifying options might involve detailed local studies and or higher level assessments using expert judgement. It is important to assess the lifetime and engineering limits of adaptations and the potential for flexibility (i.e. making adjustments over time). *No detailed appraisal of the benefits of options is carried out yet (not until step 7).*

5) Check key interactions with other issues, such as development pressures, at macro level. *For TE2100, some key potential trade-offs involved impacts on ecosystems and pressures from urban development plans.*

6) Assemble high level route maps of response options that will tackle the thresholds. *This could include no regrets measures such as emergency response which will work through the whole range of change.*

II) Appraise Solutions:

7) Compare costs, benefits and other relative criteria (e.g. environmental impact) of each route under the most likely rate of change in extreme water level. It would also explore how the costs and benefits vary under different rates of change to gauge the circumstances under which a switch to another route might be desirable. *The exact method of appraisal can vary. In TE2100 a multi criteria approach was taken to assess the cost and benefits of differing routes.*

8) Recommend the preferred route under the most likely rate of change, along with key variables which should be monitored to assess if a switch of route will be needed in the future. *The final recommended plan for TE2100 makes the best use of the existing system and the need to decide on HLO[8] 1 or 3 by 2050.*

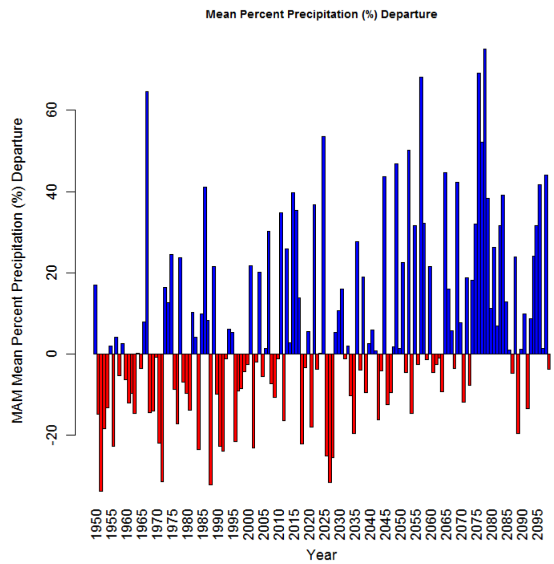
III) Implementation:

9) Implement and then monitor so you can bring things forward or put them back or change route *e.g. a significant deviation from the expected rate of sea level rise could significantly delay or accelerate the program, high rates of erosion to the defenses in the outer estuary could accelerate the need for upgraded defenses*

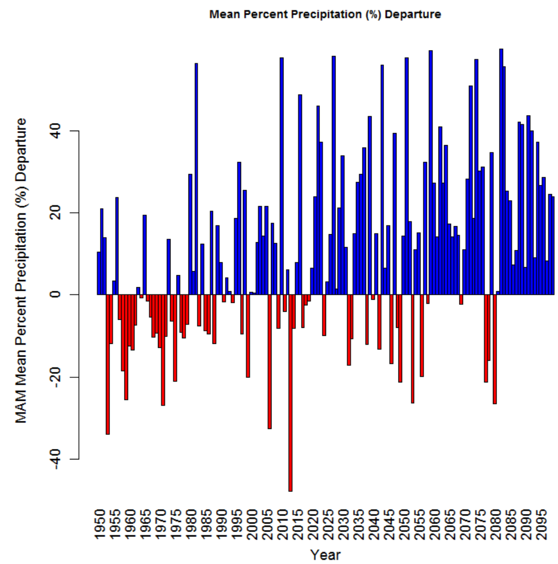
[8] High Level Options are plausible adaptation strategies that cover the full range of possible sea level rise scenarios

Appendix E: Downscaled Precipitation Model Forecasts

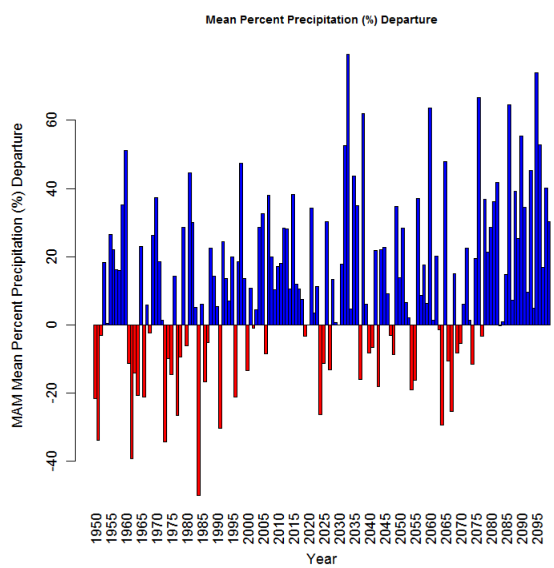
All models use the IPCC-AR4 medium (A1B) emissions scenario downscaled to the state of Vermont (ClimateWizard Custom Downscale).



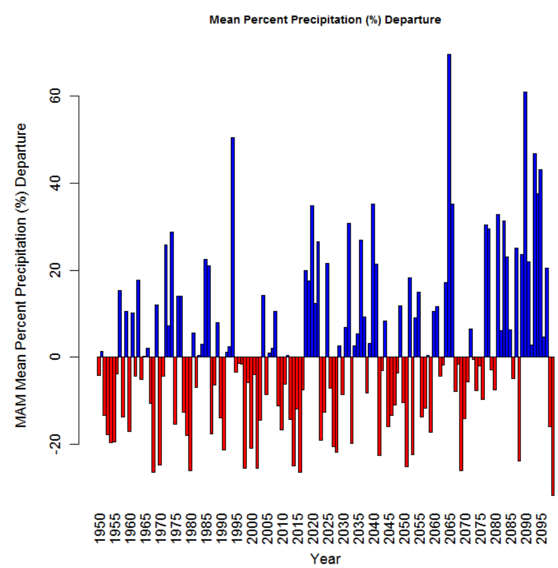
BCCR-BCM2.0



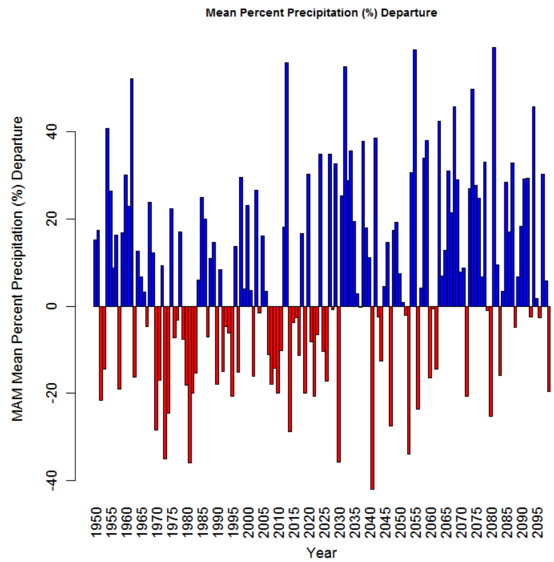
CGCM3.1 (T47)



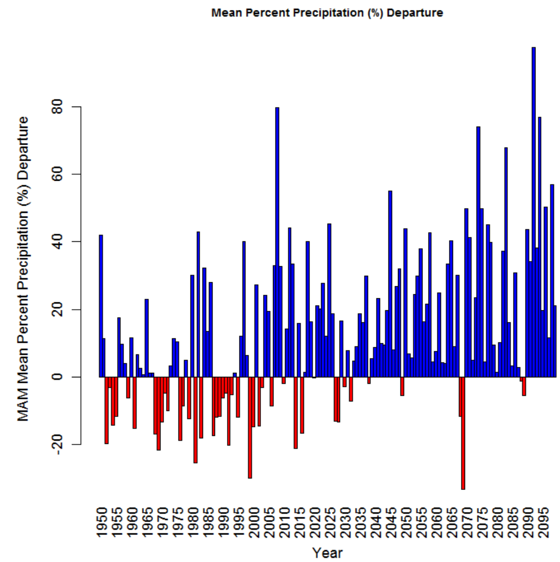
CNRM-CM3



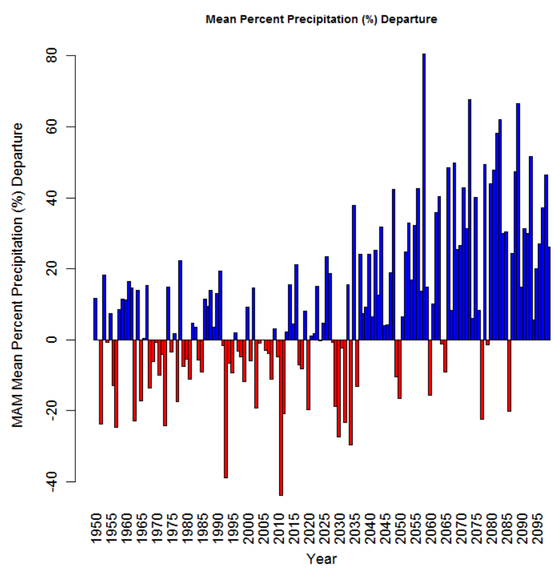
CSIRO-Mk3.0



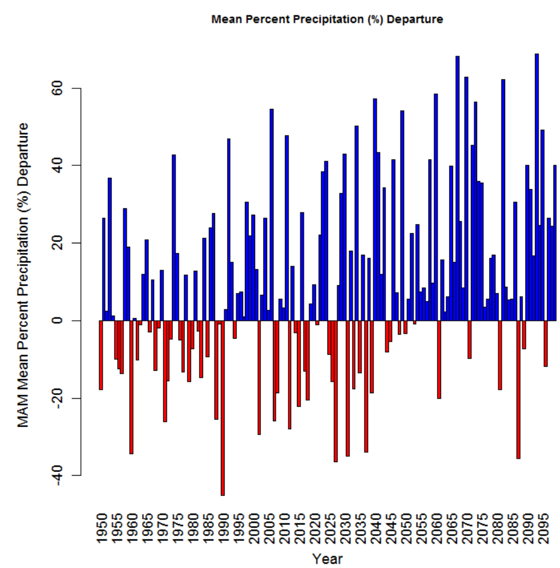
MIROC3.2 (medres)



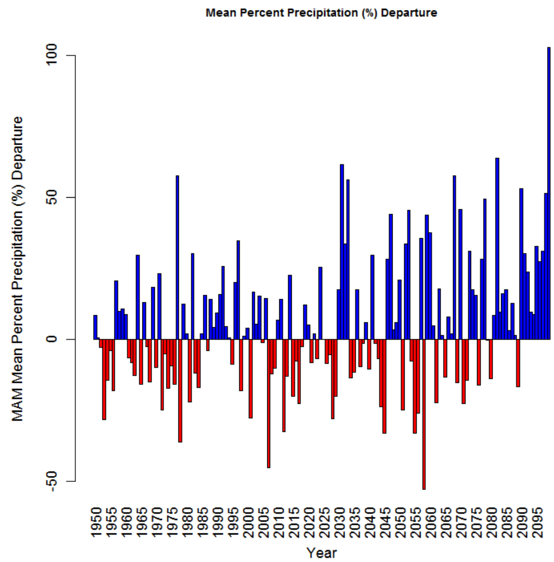
GFDL-CM2.1



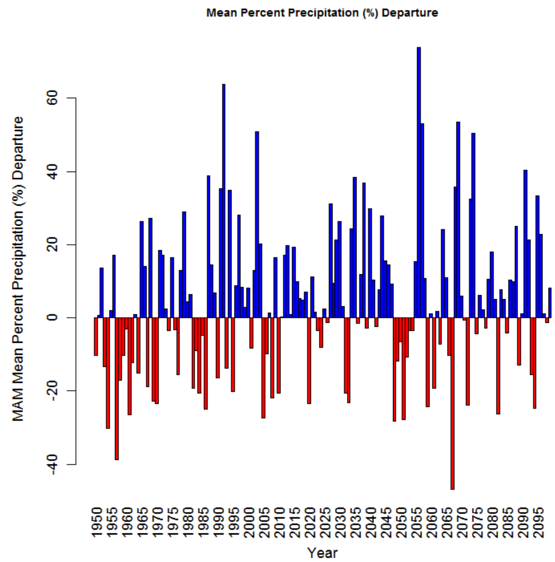
GISS-ER



UKMO-HadCM3



ECHO-G



ECHAM5/ MPI-OM

Appendix F: Compendium of Adaptation Literature

States

Estimating Future Costs for Alaska Public Infrastructure at Risk from Climate Change (June 2007)

Authors: Peter Larsen and Scott Goldsmith, Institute of Social and Economic Research (ISER), UAA Orson Smith, Civil Engineering Department, UAA; Meghan Wilson, ISER, UAA; Ken Strzepek, University of Colorado at Boulder; Paul Chinowsky, University of Colorado at Boulder; Ben Saylor, ISER, UAA; University of Alaska Foundation; National Commission on Energy Policy.; Alaska Conservation Foundation, Anchorage, Alaska; Rural Alaska Community Action Program;

Summary: This report discusses new model developed to estimate costs associated with climate change adaptation of public infrastructure in Alaska. The report provides information about how the researchers estimate costs and the difficulties of creating an accurate inventory of public infrastructure throughout the state.

http://www.iser.uaa.alaska.edu/Publications/JuneICICLE.pdf

California Infrastructure Adaptation Strategies (2010)

Authors: California Infrastructure Adaptation Strategies; Climate Adaptation Working Group (California Energy Commission and California Department of Transportation)

Summary: The state agencies that participated in the Climate Adaptation Working Group (California Energy Commission and California Department of Transportation) developed the following strategies and are responsible for and will spearhead strategy implementation . . . and will require significant changes in the planning, design, construction, operation, and maintenance of California's infrastructure. Infrastructure adaptation strategies developed thus far pertain to two aspects of development: transportation and energy.

… Adaptation plans will be developed for the long-term with estimations of future growth, demand, and vulnerability issues … areas may be identified that will need to be returned to a natural state…

http://resources.ca.gov/climate_adaptation/docs/Statewide_Adaptation_Strategy_-_Chapter_10_-_Transportation_and_Energy_Infrastructure.pdf

Transportation Planning in Response to Climate Change: Methods and Tools for Adaptation in Delaware(2012)

Authors: Oswald, Michelle; McNeil, Sue; Ames, David; Mao, Weifeng; Transportation Research Board Washington DC; Transportation Research Board 91st Annual Meeting;

Abstract Summary: As the risk of climate change increases, pressure for adaptation within transportation agencies to promote sustainable practices and alter behavior continues to rise. While mitigation efforts are essential to slowing the threat of climate change, adaptation practices to build resilience and protection from impacts should be accelerated. Implementing designs that are responsive to climate change-induced factors to reduce impacts through transportation adaptation practice is fundamental to regional transportation planning in Delaware. . .This study explores methods for analyzing potential climate change impacts such as sea level rise on transportation infrastructure in Delaware, specifically the I-95 corridor. . .The methods implemented for adaptation planning in northern Delaware provide an example of how agencies throughout the country can begin to adapt to climate change.

http://pubsindex.trb.org/view.aspx?id=1129294

Iowa Climate Change Adaptation & Resilience Report: How Should Hazard Mitigation and Other Community Planning Programs Respond to Climate Change? (2011)

Corporate Authors: Environmental Protection Agency; Federal Emergency Management Agency, WA DC; EPA;

Abstract Summary: This report presents the findings of a pilot project initiated by the U.S. Environmental Protection Agency (EPA) to work with Iowa stakeholders and governments to identify barriers to and incentives for considering regional effects of climate change in hazard mitigation planning and other community planning processes. . . Iowa communities have been experiencing floods that are growing more severe and frequent, and state and local planners are working to identify local planning approaches that improve resilience to future floods and help communities recover after disasters. . .

http://www.epa.gov/smartgrowth/pdf/iowa_climate_adaptation_report.pdf

Climate Change and Transportation in Maine (Oct. 2009)

Authors: Judy Gates, Director Maine DOT Environmental Office; Maine Department of Transportation; Oct. 14, 2009

Summary: This report from the Maine Department of Transportation describes the projected effects of climate change on transportation infrastructure in Maine. The report also discusses appropriate strategies to address the impacts. The report was issued in response to state legislation directing state agencies, businesses, industry, and other stakeholders to convene a workgroup, under the direction of the Maine Department of Environmental Protection, to address the challenges of climate change. The report also serves as a commitment to action on climate change, thus allowing MDOT access to planning funds from the Federal Highway Administration.

www.maine.gov/.../ClimateChangeandTransportationinMaine-Final.doc

Massachusetts Climate Change Adaptation Report (Sep. 2011)

Authors: Massachusetts Executive Office of Energy and Environmental Affairs; Submitted by the Executive Office of Energy and Environmental Affairs and the Adaptation Advisory Committee;

Summary: This report offers a blueprint for addressing climate change impacts in Massachusetts, including effects on natural resources and habitat, infrastructure, human health and welfare, local economies and governments, and coastal zones and oceans. The report stresses the importance of protecting infrastructure and development from inundation, especially along coasts and in floodplains, and the importance of including climate change predictions in development and design practices. The report also reviews potential strategies to enhance emergency response, to protect natural habitats and watersheds, to establish redundant supply routes, and to incorporate climate change projections into municipal planning.

http://www.mass.gov/eea/docs/eea/energy/cca/eea-climate-adaptation-report.pdf

The New Hampshire Climate Action Plan (Mar. 2009)

Authors: New Hampshire Department of Environmental Services

Summary: The Climate Action Plan outlines the infrastructure, social, and economic impacts of climate change on New Hampshire's infrastructure and economic activity.

http://des.nh.gov/organization/divisions/air/tsb/tps/climate/action_plan/nh_climate_action_plan.htm

Mainstreaming Climate Change Adaptation Strategies into New York State Department of Transportation's Operations (Oct. 2011)

Authors: David C. Major, Ph. D., Rae Zimmerman, Ph.D., John Falcocchio, Ph.D., Klaus Jacob, Ph.D., Megan O'Grady, Radley Horton, Ph.D., Daniel Bader, Joseph Gilbride, and Taylor Tomczyszyn; Columbia University Earth Institute Center for Climate Systems Research, Armstrong Hall, 2880 Broadway, New York NY; New York State Department of Transportation, Albany NY;

Abstract Summary: This study identifies climate change adaptation strategies and recommends ways of mainstreaming them into planned actions, including legislation, policies, programs and projects in all areas and at all levels within the New York State Department of Transportation (NYSDOT). . .The results of the project are presented (following the Introduction) in terms of: the current understanding of climate change science and climate futures for New York State; climate change impacts and vulnerabilities to transportation in NYS; adaptation strategies and best practices; potential adaptation strategies for mainstreaming climate change into the NYSDOT's operations and investment, including the detailed results of climate risk management discussions with personnel from 2 Divisions, 12 Offices, and 1 Region; and a communications and technology transfer plan.

https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-08-09_synthesisfinalReport1.pdf

Mainstreaming climate change adaptation strategies into NYS Department of Transportation operations: Final Report (Oct. 2011)

Authors: SPR_C-08-09; Columbia University Earth Institute Center for Climate Systems Research; New York State Department of Transportation (NYSDOT);

Summary: This study, developed by Columbia University Earth Institute Center for Climate Systems Research, identifies climate change adaptation strategies and recommends ways of mainstreaming them into planned actions, including legislation, policies, programs and projects in all areas and at all levels within the New York State Department of Transportation (NYSDOT). October 31, 2011.

https://www.dot.ny.gov/divisions/engineering/technical-services/trans-r-and-d-repository/C-08-09_synthesisfinalReport1.pdf

Report 11-18 Responding to Climate Change in New York State : The ClimAID Integrated Assessment for Effective Climate Change Adaptation in New York State – Technical Report (2011)

Authors: NYSERDA, Columbia University, the City University of New York, and Cornell University

Summary: The ClimAID assessment provides information on climate change impacts and adaptation for eight sectors in New York State: water resources, coastal zones, ecosystems, agriculture, energy, transportation, telecommunications, and public health. Observed climate trends and future climate projections were developed for seven regions across the state. Within each of the sectors, climate risks, vulnerabilities, and adaptation strategies are identified. Integrating themes across all of the sectors are equity and environmental justice and economics. Case studies are used to examine specific vulnerabilities and potential adaptation strategies in each of the eight sectors. These case studies also illustrate the linkages among climate vulnerabilities, risks, and adaptation, and demonstrate specific monitoring needs.

http://www.nyserda.ny.gov/Publications/Research-and-Development/Environmental/EMEP-Publications/Response-to-Climate-Change-in-New-York.aspx

Making Decisions: An Assessment of the Climate-Related Needs for Oklahoma Decision Makers (February 2012)

Author: Southern Climate Impacts Planning Program;

Summary: This document provides a climate needs assessment for the State of Oklahoma. The assessment finds that Oklahoma will be subject to rain events that are less frequent but more intense, increasing the risk of drought and floods. The assessment also identifies the types of information that long-range planners, including transportation planners, will need to effectively address climate impacts. The SCIPP is a National Oceanic and Atmospheric Administration regional integrated sciences and assessment team. Findings resulted from interviews with state decision makers conducted by the University of Oklahoma and Louisiana State University.

http://www.southernclimate.org/publications/OK_Climate_Needs_Assessment_Report_Final.pdf

ODOT's Climate Change Adaptation Strategy Report(April 2012)

Authors: Liz Hormann, ODOT; ODOT Climate Change Technical Advisory Committee; Oregon Department of Transportation;

Summary: This report from the Oregon Department of Transportation provides an assessment of potential climate change impacts to ODOT; underscores the need for an in-depth vulnerability and risk assessment of ODOT's assets and systems operations; and highlights potential adaptation strategies and existing adaptive capacity within ODOT. http://www.oregon.gov/ODOT/TD/CLIMATECHANGE/docs/ODOT_Adaptation_Strategy_Final.pdf

Identifying Surface Transportation Vulnerabilities and Risk Assessment Opportunities Under Climate Change: Case Study in Portland, Oregon (2011)

Authors: Lindsay Walker, Miguel A. Figliozzi, Ashley R. Haire, and John MacArthur, Portland State University, Oregon Transportation Research and Education Consortium;

Summary: This article discusses a method for transportation departments, using geographic information systems, to assess the vulnerability to climate change of various multimodal surface transportation systems. Using Portland, Ore., as a case study, the study outlines how climate change effects can be identified, prioritized, and their impacts assessed. http://trb.metapress.com/content/pv122013607m1k84/?p=703e6f75aa74408bac23cb3409252510&pi=5

Oregon Climate Change Adaptation Framework (Dec. 2010)

Authors: Oregon DOT;

Summary: _The purposes of this framework are to a) identify likely future climate conditions that pose some risk for Oregonians; b) assess the capacity of state programs to effectively address climate-related risks to people, communities, infrastructure, and natural resources; c) Identify short-term priority actions to prepare for those risks; and d) Provide context and initial direction for additional coordination and planning for future climate conditions.

http://www.oregon.gov/energy/GBLWRM/docs/Framework_Final_DLCD.pdf

Pennsylvania Climate Adaptation Planning Report: Risks and Practical Recommendations (Jan. 2011)

Author: Pennsylvania Department of Environmental Protection;

Summary: This report represents the first statewide effort to identify practical strategies for addressing climate change impacts. The report includes the recommendations for climate change adaptation of four sector-specific working groups established by DEP and the state Climate Change Advisory Committee: Infrastructure, Public Health and Safety, Natural Resources, and Tourism and Outdoor Recreation. Recommended actions for the transport sector include reviewing research for materials that have the potential to withstand higher temperatures to prevent buckling of roadways and bridges and performing more intense inspections of transportation infrastructure after high impact events in areas subject to erosion. Cross-cutting recommendations include adopting green infrastructure, walkable communities, and integrating adaptation and mitigation strategies as part of government agency planning and operations.

http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-82988/7000-RE-DEP4303%20combined%20report.pdf

Impacts of Climate Variability and Change on Transportation Systems and Infrastructure – Gulf Coast Study (Mar. 2008)

Authors: Savonis, M. J.; V.R. Burkett; and J.R. Potter (eds.); USDOT;

Summary: The research, sponsored by the U.S. Department of Transportation (DOT) in partnership with the U.S. Geological Survey (USGS), was conducted under the auspices of the U.S. Climate Change Science Program (CCSP). This report . . . describes ways to incorporate climate change issues into transportation planning. The major drivers of climate change examined in the report are sea levels rise, warming temperatures, precipitation pattern changes, and increased intensity of storm activity.

http://www.climatescience.gov/Library/sap/sap4-7/final-report/

Europe

Infrastructure, Engineering and Climate Change Adaptation – Ensuring Services in an Uncertain Future (2011)

Corporate Authors: Royal Academy of Engineering, 3 Carlton House Terrace London, UK; Institution of Chemical Engineers; London, UK; Institution of Engineering and Technology; Stevenage, England; Institution of Mechanical Engineers; London, England;

Abstract Summary: This report investigates sectors of infrastructure in the United Kingdom that may be vulnerable to the impacts of climate change. It explores the actions necessary to increase the flexibility and resilience of these infrastructure sectors. It also examines the ways in which the different infrastructures are interdependent, and how that impacts infrastructure vulnerability and risks. Adaptation to climate change is viewed in the light of two issues - long term impacts such as rising sea level, and extreme events, such as flash floods. . . Electric grids and smart grids are offered as examples of infrastructure interdependence.

http://www.raeng.org.uk/news/publications/list/reports/Engineering_the_future_2011.pdf

Climate Change Adaptation: A Report on Climate Change Adaptation Measures for Low Volume Roads in the Northern Periphery (Sweden, Norway & Finland) (2012)

Authors: Adriána Hudecz, Arctic Technology Centre (ARTEK) at the Technical University of Denmark (DTU); ROADEX; Swedish Transport Administration; The ROADEX "Implementing Accessibility";Lead Partner: The Swedish Transport Administration, Northern Region; Project co-coordinator: Mr. Krister Palo;

Summary: … The report summarizes recent published researches on climate change and its possible impact on low volume roads in the Northern Periphery. Its aim was to produce a practical guidance document for local engineers to help them to manage potential effects of climate change on their local road networks.

. . . The report concludes with an appendix of recommended of good practice and adaptation measures.

http://www.roadex.org/uploads/publications/Climate%20Change%20Adaptation%20(2012).pdf

The costs of extreme weather for the European transport systems, EWENT project D4 (2012)

Author: VTT Technical Research Centre of Finland,

Summary: The report provides concrete monetary valuations of the impact of extreme weather phenomena on the transport system. This target is operationalized through several steps of research activities: Review of methodologies used to value accidents and travel time savings; Determination of values used; Justification of values chosen; Calculations of impacts, measured in euro; Mode by mode analysis of what cost items are significant; Analysis of data availability and needs for additional data for future analysis

http://www.vtt.fi/inf/pdf/technology/2012/T36.pdf

Scotland's Climate Change Adaptation Framework – Transport (Dec. 2009)

Summary: This provides an overview of key issues in adapting to the consequences of climate change for this sector. Actions outlined in this summary provide an indication of the broad range of work planned over the coming years to strengthen resilience of this sector to the impacts of climate change. These actions are an illustration rather than an exhaustive list.

http://www.scotland.gov.uk/Publications/2009/12/08131211/1

How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project (2011)

Authors: Tim Reeder (UK Environment Agency),Nicola Ranger (Grantham Research Institute on Climate Change and the Environment and the Centre for Climate Change Economics and Policy, London School of Economics and Political Science);

Summary: This paper outlines one approach to tackle uncertainty that aims to ensure that adaptation decisions made today are resilient to a fast changing and uncertain climate. The approach, based on a developing a simple 'route-map' of adaptation options, has been demonstrated in practice in the Thames Estuary 2100 (TE2100) project for London. The UK Environment Agency's TE2100 project provides a real-life example of adaptation decision making under uncertainty applied to a long-lived infrastructure decision with high sunk-costs. There is an overview of lessons learned during TE2100 to demonstrate how such large-scale decisions can be made robust in the face of deep uncertainty over future climate using a route-map approach.

http://www.worldresourcesreport.org/files/wrr/papers/wrr_reeder_and_ranger_uncertainty.pdf

Adaptation as a Decision Making under Deep Uncertainty: a unique challenge for policymakers? (2011)

Author: Nicola Ranger

Summary: This document is an academic economic approach to decision making under deep uncertainty. Ranger outlines a decision-making framework to avoid potential barriers to adaptation and possibilities of potential maladaptation.

http://www.springerlink.com/content/m2w1183524116147/

Adaptation in the UK: a decision making process (2010)

Author: Nicola Ranger, Antony Millner, Simon Dietz, Sam Fankhauser, Ana Lopez and Giovanni Ruta

Summary: An in-depth application of Ranger's context-first decision-making framework to several case-studies including flooding in the UK, the UK water sector, the UK food sector, and ecosystems and biodiversity

Report:

http://personal.lse.ac.uk/RANGERN/PB-adaptationUK-rangeretal.pdf,

Annexes:

http://personal.lse.ac.uk/RANGERN/PB-technical-annexes-rangeretal.pdf

Australia & New Zealand

Barriers to Effective Climate Change Adaptation – Draft Report [(AU, Apr. 2012) Final report expected Sep. 2012)

Author: Australia Productivity Commission

Summary: assess the regulatory and policy barriers to effective adaptation. In undertaking the review, the Commission should identify any specific barriers that may act to inhibit effective adaptation to unavoidable climate change.

The Commission should identify high priority reform options to address any identified barriers to effective adaptation. The Commission should also: a)examine the costs and benefits of the options to address those barriers where it is feasible to do so, including a 'no change' (maintaining the status quo) option; and b) assess the role of markets (including insurance markets) and non-market mechanisms in facilitating adaptation, and the appropriateness of government intervention.

http://www.pc.gov.au/projects/inquiry/climate-change-adaptation/draft

A risk management approach to climate change adaptation (NZ, 2010)

Author: Roger Jones (Centre for Strategic Economic Studies, Victoria University, Melbourne, Victoria, Australia)

Summary: This document addresses risk management techniques to assess adaptation options. It suggests integrating standard climate impact assessment with predictive and diagnostic approaches, the use of planning horizons linked to types of adaptation, and likelihoods expressed as the probability of exceeding a given level of outcome are proposed as methods to improve decision-making.

http://www.nzclimatechangecentre.org/sites/nzclimatechangecentre.org/files/images/research/Climate%20Change%20Adaptation%20in%20New%20Zealand%20%28NZCCC%29%20high%201.pdf

Tools for Estimating the Effects of Climate Change on Flood Flow A Guidance Manual for Local Government in New Zealand (May 2010)

Author: New Zealand Climate Change Office, Ministry for the Environment

Summary: This document provides communities with a) information on the key effects of climate change on flood risk, b) methods for estimating changes in the frequency and/or magnitude of rainfall, c) methods for converting changes in rainfall to changes in flow rate, d) methods for converting changes in flow rate to changes in inundation, and e) some case studies to illustrate these methods.

http://www.mfe.govt.nz/publications/climate/climate-change-effects-on-flood-flow/

A Methodology to Assess the Impacts of Climate Change on flood risk (Jul. 2005)

Author: New Zealand Climate Change Office, Ministry for the Environment

Summary: These materials provide information on climate change impacts as well as a generic risk assessment framework that can apply to flood risk as well as to other weather-related natural hazards. This report provides more specific guidance for councils on how to handle the possible impact of climate change when assessing flood risk. Firstly, a simple screening test is recommended to assess whether climate change is likely to significantly affect flooding in a region. If so, it is recommended that a further, more detailed analysis be carried out for each catchment of interest. More accurate projections of expected future flood risk will provide local government with a better basis for community consultation and informed decision-making on necessary levels of flood protection works. This report first outlines the application of the screening test, which will help councils identify whether changes in flood risk are likely to be significant. It then outlines a more detailed methodology to assess the impacts of climate change on flooding. The methodology involves using weather models to estimate the impact of expected temperature changes on future rainfall. The weather models generate estimates of the future rainfall. Hydrological modeling is then used to convert future rainfall to future river flows, including peak flow levels. Finally, inundation models can be used to convert that peak flow to the area, depth, and flow speed of flood waters. Many councils are already using hydrological and inundation modeling when assessing current flood risk for their communities. The methodology described here to assess the impacts of climate change fits well into this more general framework.

http://www.mfe.govt.nz/publications/climate/impact-climate-change-flood-risk-jul05/

Preparing for future flooding: A guide for local government in New Zealand (May 2010)

Author: New Zealand Climate Change Office, Ministry for the Environment

Summary: A short 30 page summary of *A methodology to Assess the Impacts of Climate Change on Flood Risk* (Jul. 2005) and *Preparing for future flooding: A guide for local government in New Zealand* (May 2010)

www.mfe.govt.nz/publications/climate/preparing-for-future-flooding-guide-for-local-govt/

General Adaptation

Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges (May/June 2012)

Authors: AASHTO Workshop and Webinar; American Association of State Highway Transportation Officials;

Summary: AASHTO hosted a webinar June 27, 2012 to provide an overview of a workshop on adapting infrastructure to extreme weather held in conjunction with AASHTO's spring meeting in May 2012. The workshop, titled Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges, provided information on approaches to evaluating and mitigating the impacts of extreme weather events on transportation infrastructure. State DOT officials from across the country discussed their recent experiences with extreme weather impacts and shared perspectives on how to manage weather-related risks. The webinar featured case studies of efforts by the state DOTs in California, Iowa, and Washington to address adaptation issues and speakers described challenges and barriers state DOTs face in addressing those issues.

workshop summary report:

http://climatechange.transportation.org/pdf/aashto%20infrastructure%20adaptationworkshopsummary6-26-12.pdf

background white paper:

http://climatechange.transportation.org/pdf/aashto%20infrastructure%20adaptationworkshopsummary6-26-12.pdf

webinar power point presentations:
http://climatechange.transportation.org/pdf/aashto_adaptation_webinar_6-27-12.pdf

Climate Change Vulnerability Assessment Pilot: Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual (2012)

Authors: Federal Highway Administration; FHWA CC Website;

Summary: This document outlines a conceptual Risk Assessment Model that will be piloted by three to four State Departments of Transportation (DOTs) or Metropolitan Planning Organizations (MPOs) (hereafter, "transportation agencies") selected by the Federal Highway Administration (FHWA). Using feedback and lessons learned during this pilot phase, FHWA will refine this draft conceptual model and develop a final version for all transportation agencies.

The goal of the Risk Assessment Model is to help transportation decision makers (particularly transportation planners, asset managers, and system operators) identify which assets (a) are most exposed to the threats from climate change and/or (b) are associated with the most serious potential consequences of those climate change threats.

http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/conceptual_model62410.cfm

Climate Change Adaption for Sustainable Transportation Systems (April 25, 2012)

Author: Art Hirsch; TerraLogic Transportation Blog;Wednesday,

Summary: …New research shows that if present trends continue, the total cost of global warming will be as high as 3.6 percent of gross domestic product (GDP). Four global warming impacts alone -- hurricane damage, real estate losses, energy costs, and water costs -- will come with a price tag of 1.8 percent of U.S. GDP, or almost $1.9 trillion annually (in today's dollars) by 2100 (1).

. . . It is important that new transportation and other infrastructure projects are designed with flexibility and resiliency to accommodate climate change’s short and long term impacts. Climate change needs to be part of the long term thinking for transportation planning, design, and operation and maintenance of transportation systems.

http://terralogicss.com/_blog/Sustainable_Transportation/post/Climate_Change_Adaption_for_Sustainable_Transportation_Systems/

Transportation Impacts & Adaptation: Climate Impacts on Transportation (2012)

Authors: US EPA; USDOT;

Summary: The report indicates: Climate change is likely to damage transportation infrastructure through higher temperatures, more severe storms, and higher storm surges. Coastal roads, railways and airports are vulnerable to sea level rise, which could lead to delays as well as temporary and permanent closures. Warmer winters can alleviate the costs of clearing ice and snow, especially in northern areas.

In the United States, transportation systems are designed to withstand local weather and climate. Transportation engineers typically refer to historical records of climate, especially extreme weather events, when designing transportation systems. For example, bridges are often designed to withstand storms that have a probability of occurring only once or twice every 100 years. However, due to climate change, historical climate is no longer a reliable predictor of future impacts.

http://www.epa.gov/climatechange/impacts-adaptation/transportation.html

Adapting to Climate Change: Another Challenge for the Transportation Community (2011)

Authors: Schwartz Jr., and Henry G; Serial: Transportation Research E-Circular; Issue Number: E-C152

Abstract Summary: … This paper does not address the science of climate change or the issue of mitigation to reduce the emissions of greenhouse gases (GHG). Rather it accepts the current state of knowledge on global warming and focuses on adaptation. How does the transportation community develop solutions and approaches that will minimize or eliminate the impact of climate change? . . . While most of these scenarios deal with transportation, a few others are included to demonstrate the breadth of the impacts.

http://onlinepubs.trb.org/onlinepubs/circulars/ec152.pdf

Adapting Transportation to the Impacts of Climate Change: State of the Practice 2011 (2011)

Authors: Wenger, Joyce; Serial: Transportation Research E-Circular, Issue Number: E-C152;

Publisher: Transportation Research Board; 2011

Abstract Summary: … This document focuses on transportation adaptation practices that can be implemented to yield benefits now and in the longer term. It highlights what climate change adaptation means for the transportation industry and why it is so important.

http://onlinepubs.trb.org/onlinepubs/circulars/ec152.pdf

Educating the Public on Climate Change Issues: DOT and MPO Best Practices (June, 2010)

Authors: ICF International, Washington, DC; Federal Highway Administration, U.S. DOT;

Summary: This document summarizes outreach activities and public education initiatives used around the country by State Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) to educate the public on transportation-related climate change issues. (PDF - 129Kb.)

http://www.fhwa.dot.gov/environment/climate_change/adaptation/resources_and_publications/educating_the_public/index.cfm

Regional Climate Change Effects: Useful Information for Transportation Agencies (May, 2010)

Authors: ICF International, Washington, DC; Federal Highway Administration, U.S. DOT;

Summary: This document provides information on projected future climate change effects (changes in temperature, precipitation, storm activity and sea level rise) over the near term, mid-century and end-of-century. The report includes two appendices: maps for some of the climate change effects, and a "typology" of projected climate change information gleaned from recent reports. http://www.fhwa.dot.gov/environment/climate_change/adaptation/resources_and_publications/climate_effects /

The Implications of Climate Change on Pavement Performance and Design (2011)

Authors: Li, Qiang; Mills, Leslie; McNeil, Sue; Corporate Authors: Delaware Center for Transportation Newark, DE; Research and Innovative Technology Administration; Washington DC; Delaware Center for Transportation, Newark, DE; 2011

Abstract Summary: … This research explores the impacts of potential climate change and its uncertainty on pavement performance and therefore pavement design. Two tools are integrated to simulate pavement conditions over a variety of scenarios. . .Three test sites in the North Eastern United States are studied and the framework is applied. It demonstrates that the framework is a robust and effective way to integrate climate change into pavement design as an adaptation strategy.

http://www.ce.udel.edu/UTC/20110926_FinalReport_Pavement_ClimateChange.pdf

Ongoing Work

Successful Adaptation: Identifying Effective Process and Outcome Characteristics and Practice-Relevant Metrics (ongoing)

http://cses.washington.edu/cig/res/hd/successfuladaptation.shtml

Caltrans Climate Change Adaptation Hot Spot Map (ongoing)

http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change_projects_and_studies.html

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