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CITIES AND COMMUNITIES: THE CHANGING CLIMATE AND INCREASING VULNERABILITY OF INFRASTRUCTURE

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1. Introduction

Infrastructure is critically important to individuals and to communities. The purpose of infrastructure is to protect the life, health, psychological and social welfare of all of its inhabitants from the weather elements, to host economic activities and to sustain aesthetic and cultural values. Infrastructure—including houses, hospitals, schools, factories, roads, bridges, communications structures, power distribution networks, water structures—supports communities and economic activities, provides important life services for individuals and families, and protects society's cultural heritage. When infrastructure fails under extreme weather conditions and can no longer provide services to communities, the result is often a natural disaster (Freeman and Warner, 2001). As the climate changes, it is likely that risks for infrastructure failure will increase worldwide as weather patterns shift and extreme weather conditions become more variable and regionally more intense. Because infrastructure underpins so many of the economic activities of societies, these impacts will be significant and will require a variety of adaptation actions (Dalgliesh, 1998; Holm, 2003; Lowe, 2003).

Compared to the decade of the 1950s, the annual direct losses from large or globally significant natural catastrophes in the 1990s increased over 10 times[1], rising from US$3.9 billion to US$40 billion a year in 1999 dollars (Munich Re, 2000; IPCC, 2001a), while population grew only by 2.4-fold. Most of the increases in losses were the result of weather-related high impact events. Of total losses averaging $40 billion a year, approximately $9.6 billion of direct damage occurred as a result of infrastructure losses (Freeman and Warner, 2001). In the case of flood losses, some estimates indicate that infrastructure failure and loss accounted for 65% of all flood losses (Swiss Re, 1997a). While total disaster losses can

[1] These costs are larger by a factor of two when losses from relatively ordinary weather-related events are included.

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vary considerably from year-to-year, notable losses were reported in 1995 when, based on historical data, infrastructure losses alone totalled some $33 billion (Munich Re 1999). For example, studies undertaken by the Norwegian Building Research Institute (Ingvaldsen, 1994; Liso et al, 2003) indicate that the cost of repairing damages to structures in Norway from storm events is estimated at about 5% of the annual investment costs for new construction, amounting to NOK $4 billion annually in Norway alone. Although an increase in the number and intensity of storms regionally may play a role in these disasters, there is no question that a significant portion of the increasing costs are also the result of increased vulnerability (Pielke and Downton, 2000; Auld and MacIver, 2004).

One of the most threatening aspects of global climate change is the likelihood that extreme weather events will become more variable, more intense or more frequent, leading to catastrophic losses. The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001a) states that:

> *"The key features of climate change for vulnerability and adaptability are those related to variability and extremes, not simply changed average conditions. Most sectors and regions are reasonably adaptable to changes in average conditions, particularly if they are gradual. However, these communities are more vulnerable and less adaptable to changes in the frequency and/or magnitude of conditions other than average, especially extremes". (Chapter 18, page 879)*

According to the Intergovernmental Panel on Climate Change (IPCC, 2001a), extreme weather events may occur more frequently, at least regionally, with the potential to affect flooding, droughts and the frequency and severity of cyclonic systems (including hurricanes). Factors such as changing winds or storm tracks might offset this effect at the local level. In all cases, changes in climate will require changes to the criteria for the design of infrastructure, as well as larger societal and sectoral changes. The structures built in earlier times will remain robust under current and future conditions if extremes decrease, while those designed for earlier and lower extremes will come under greater risk of collapse if extremes increase. Overall, it is reasonable to expect that infrastructure damage will increase exponentially as a portion of total losses with changing extremes. According to a report by the United Nations Environment Programme's (UNEP), the global costs of natural disasters are anticipated to increase significantly and to top US$300 Billion by the year 2050 if the likely impact of climate change is not countered with aggressive disaster reduction measures (Berz, 2001; UNEP, 2001). Infrastructure's share of this annual total could reach at least 25% of the total or about $80 billion each year (Freeman and Warner, 2001).

2. Infrastructure and Climate Adaptation Requirements

Because the Building, Construction and Property Services Sector is claimed to be the world's largest sector, at least for industrialized countries (Holm, 2003), any increase in extreme events will have significant economic and social impacts. In developing countries, changes in extreme events have the potential to cause even greater disruption to communities and to significantly impact future development.

The impacts of climate change on infrastructure and the built environment will require unique adaptation options due to the complexities associated with the construction sector and the uncertainties in the climate change information needed to inform adaptation decisions. For example, adaptation options will need to consider the following realities:

- Infrastructure typically has long lifetimes, with many structures expected to be still standing at the end of this century. Buildings, for example, are often designed with the intention that they remain stable for 50-60 years (Steemers, 2003a);

- The robustness of the existing stock of infrastructure is variable, with structures constructed to withstand varied extreme climate and weather conditions, depending on the age and type of structure, its maintenance record and the "margins of safety" used;

- Structures and their materials are aging and in many regions, infrastructure has not been replaced or maintained at sustainable rates. As a result, the proportion of the infrastructure that is vulnerable to extremes and to "weathering" processes is increasing. Regionally, infrastructure is also deteriorating prematurely or at accelerating rates due to the changing physical and chemical atmosphere (Holm, 2003);

- Many existing buildings and communities are located in vulnerable locations, including exposed coastal zones and river flood plains, and more rigorous disaster management planning will be required;

- The construction industry, building codes and standards and land use planning all have historically remained slow to change;

- Land use and building materials decisions are often dominated by short-term commercial interests rather than long-term risk requirements.

Current understanding of the potential impacts of climate change on infrastructure is still very limited and further research and development will be required to support decision-making. While a few studies are emerging from a handful of countries, most of these studies are based on generalities and on broad large-scale analyses. Among the challenges, there is a critical need for research to fill in the gaps between regional climate impacts and the requirements for designing infrastructure to withstand the climates of today and the future. More specific information is needed to determine which types of infrastructure and which regions are likely to experience the greatest losses in future and to develop climatic design information that minimizes additional risks for structures long into the future.

3. Weather Extremes and Designing Against Infrastructure Damage

As the climate changes, it is expected that small increases in weather and climate extremes will have the potential to bring large increases in damages to existing infrastructure. Studies indicate that damage from extreme weather events tends to increase dramatically above critical thresholds, even though the high impact storms associated with these damages may not be much more severe than the type of storm intensity that occurs regularly each year (Munich Re., 1997; Swiss Re., 1997a; Coleman, 2002). In many cases, it is likely that the critical thresholds reflect storm intensities that exceed average design conditions for a variety of infrastructure of varying ages and condition. An investigation of claims by the Insurance Australia Group (IAG), as shown in Figure 1, indicates that a 25% increase in peak wind gust strength can generate a 650% increase in building claims (Coleman, 2002). Similar studies indicate that once wind gusts reach or exceed a certain level, entire roof sections of buildings often are blown off, or additional damages are caused by falling trees. Typically, minimal damages are reported below this threshold (Munich Re., 1997; Swiss Re., 1997a; Freeman and Warner, 2001; Coleman, 2002).

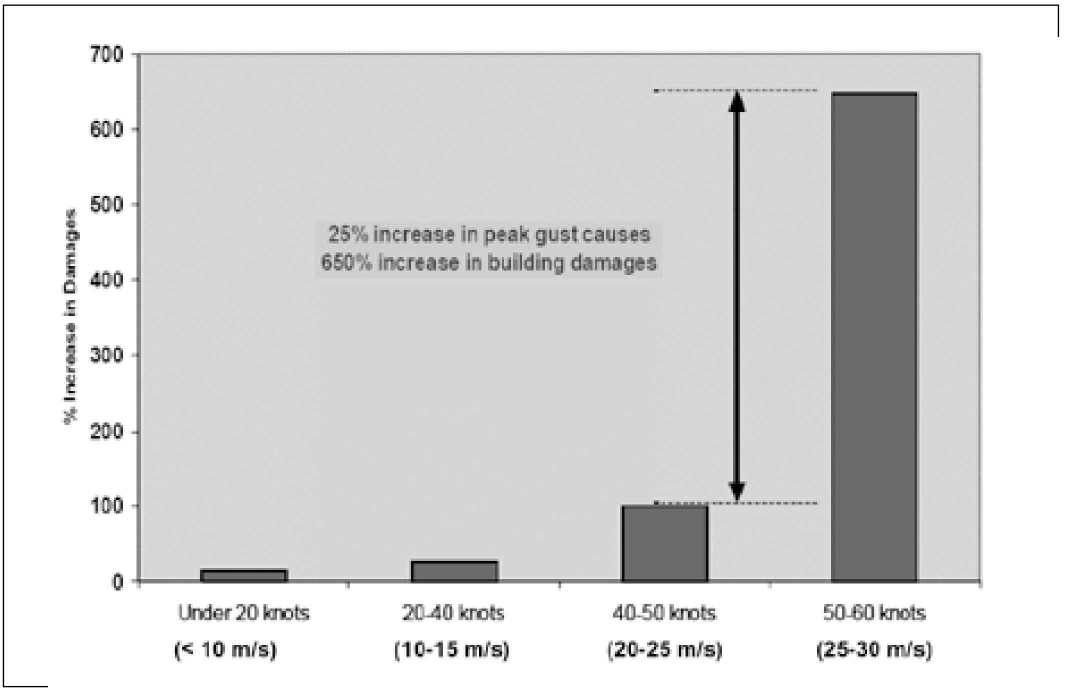

Figure 1: Source: (Coleman, 2002). IAG Building claims as a function of peak gust speed.

The quality of construction and the maintenance of structures will strongly influence the damages and extent of claims. Figure 2 shows typical vulnerability curves for various quality of construction, where mean marginal damage from windstorms increases exponentially with local peak wind gust velocities (Swiss Re, 1997a). The curves reflect substandard quality, standard quality and high quality construction (bottom curve), respectively. Hence, as shown in Figure 2, moving from a wind speed of 40 meters per second to a speed of 60 meters per second increases marginal damage from about 2 to 10 percent (standard construction). For buildings of substandard quality, an increase in wind speed from 60 meters per second to 80 meters per second increases losses from 10 percent to 75 percent (Swiss Re, 1997a). As wind speed increases, minor changes in velocity can drive up damage significantly. It is obvious that lower quality construction or poor maintenance over time rapidly worsens marginal damage.

Similar results have been obtained for flood and hailstone damages. For example, hailstones below a certain size have been found to not damage car panels whereas above this critical size, damage

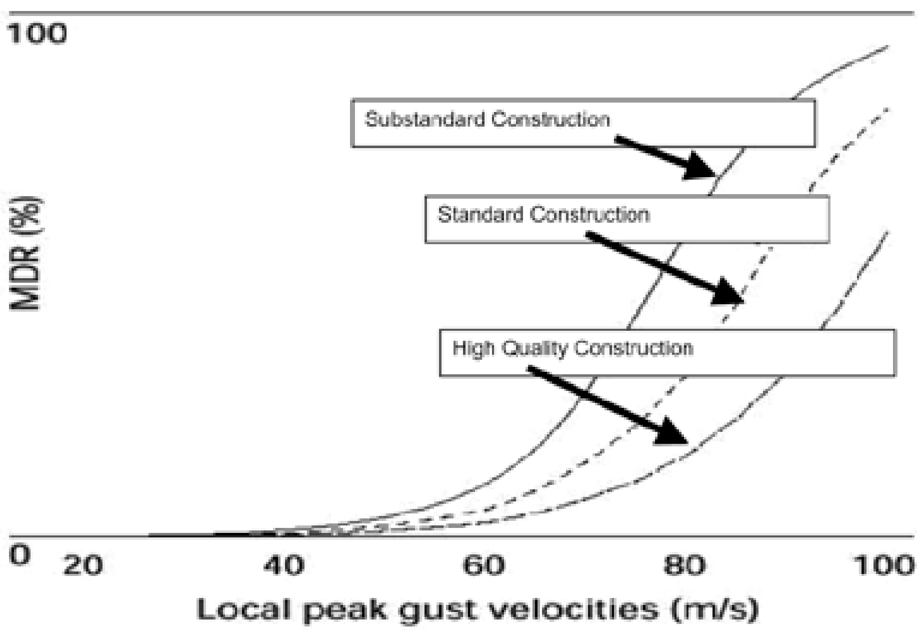

Figure 2: Source: (Swiss Re, 1997a). Relative mean marginal building damages (%) as a function of peak wind gust velocities for varying quality of construction. *The results indicate, for example, that a 20 meter per second increase in wind speed can increase damages by 65%.*

increases abruptly (Freeman and Warner, 2001). Likewise, similar damage curves exist for flood damage events (Munich Re 1997; Swiss Re 1998), indicating that a small increase in flood levels may vastly increase flood damage as incremental flood levels overwhelm existing infrastructure and flood protection systems. In general, flooding, ice storm and wind storm events tend to result in the most widespread, costly and direct impacts to infrastructure such as buildings, bridges, roads, communications, electricity generation and water systems.

Globally, droughts are one of the most costly of all disasters worldwide, capable of bringing massive economic losses, destruction of ecological resources, food shortages and starvation for millions of people in developing nations (IPCC, 2001a). Climate change projections of more frequent and intense drought conditions will affect demands on water distribution infrastructure and impact soil stability for other types of infrastructure. For example, more frequent and intense droughts will likely increase incidences of soil and infrastructure subsidence, requiring more adaptation actions in the form of widespread structural underpinning, tree removals near building foundations, deeper foundations for new structures and redesign of foundations with increased stiffness (Sanders and Phillipson, 2003).

Climate Change and Engineering Codes and Standards

In many countries, structures are designed using national building codes and infrastructure standards. These codes and standards depend on a set of climatic and seismic design values, where values can vary considerably from one location to another. Almost all of today's infrastructure has been designed using climatic design values calculated from historical climate data under the assumption that the average and extreme conditions of the past will represent conditions over the future lifespan of the structure. While this assumption has worked in the past, it will no longer hold as the climate changes. Until the uncertainty in climate change scenarios are reduced, it will become critically important that climatic design values be regularly updated to reflect the changing climate and that deficiencies in existing climatic design values be improved, with uncertainties reduced as soon as possible.

Typically, decisions on how to build structures are primarily driven by the need to build both safely and economically. The appropriate balance must be struck between safety and required strength and serviceability over the life of the structure and over initial and maintenance costs. This balance can only be achieved using realistic estimates of future climatic design loads. While structures can always be "over-designed" to protect against natural hazards, the economic costs to societies can prove prohibitive.

Climatic design values include quantities like the 10, 50, or 100 year return period “worst storm” wind speed, rainfall or weight of snowpack conditions that are typically derived from historical climate data. Other climatic design quantities include percentile cold, hot or humid temperature or humidity conditions return period ice accretion loads and average degree day quantities. A given return period storm does not mean that the design storm only occurs once in the named time frame but refers to the risk of an event being reached or exceeded in a period. A 50 year return period wind storm speed, for example, refers to a one chance in 50 wind speed that can be expected to be reached or exceeded in any year. On average, a 50 year return period storm has a 64 percent chance of being reported at least once in a given 50-year period, a 26 percent chance of occurring twice and an 8 percent chance of at least three occurrences in a 50-year time period (Cook, 1985). In essence, there is about a one in twelve chance of at least three storms with wind speeds equal to or greater than the 50-year design speed occurring within a given 50 year period.

Structural failures can result when climate extremes approach their design values and the engineering performance of the structure encroaches or exceed design uncertainty limits. The design of structures requires an appreciation of the variability and uncertainty of the engineering technology. For critical post-disaster buildings such as schools and hospitals, basic engineering loads are augmented by greater safety factors that account for uncertainties in strengths of materials and uncertainties in other engineering technologies (Canadian Commission on Building and Fire Codes, 1995). However, safety or uncertainty factors are not necessarily assigned to the climatic design values, with the implicit assumption being that these values are relatively stable. In reality, climatic design values derived from extreme climate statistics can be subject to considerable uncertainty due to data and other constraints, as discussed in Section 6.

The choice of safety factor used depends upon the intended occupancy or use of the structure. The greater the number of people expected to use or be impacted by the structure, the safer the design must be. Transmission lines, for example, are designed with lower safety factors since their failures are considered to bring economic losses rather than losses of lives while critical post disaster buildings, such as hospitals or schools, are designed with higher safety factors. However, with increasing trends towards electronic and “just in time” delivery economies, the losses from interruptions in power now include large economic costs as well as losses of lives. The severe Ice Storm of January, 1998, that caused failures and interruptions to electricity distribution systems in eastern Canada and the northeastern U.S. also led to loss of lives from ice hazards, exposure, an inability to heat buildings, road accidents and poisoning from use of temporary heaters. It seems likely that, as societies become increasingly dependent on critical infrastructure services and increasingly vulnerable to interruptions created by weather and climate extremes, the safety factors in use in codes and standards will need to be assessed and potentially revised. This assessment will be particularly important for the more critical infrastructure components.

Until the uncertainties associated with the directions and magnitudes of changes in climate extremes are known and can be incorporated into climatic design values able to consider current and future climate conditions, the safety factors used in codes and standards may need to be increased to reflect the growing uncertainties in climatic conditions over the lifespan of the structure. Since uncertainty is well accepted as a part of construction codes and standards and the regulatory process, it should be possible to deal with the growing uncertainty of future climate design values through measures such as increasing safety factors (Dalgliesh, 1998; Sanders and Phillipson, 2003). While regulators and the construction industry will undoubtedly be reluctant to include significant improvements and resultant increases in the costs of construction, the reality is that engineering and regulation are already based on statistical analyses of risk. Uncertainty over the future climate is one more source of variance or uncertainty that can be quantified by various methodologies (e.g. variances from different climate models). Improvements in downscaling methodologies and the development of climate change analyses techniques more appropriate for climate extremes (e.g. statistical map typing methodologies, decision modelling) will also improve confidence in projections of climate change impacts and their implications for climatic design values.

Under current processes, building codes and other infrastructure standards are typically slow to change, particularly since industry stakeholders often resist new changes that add to the costs of structures. Because new or replaced infrastructure will come to play an increasingly important role in building adaptive capacity, particularly when compared to the cost of retrofitting existing infrastructure, it is important to ensure that infrastructure is optimally adapted as soon as possible for existing and future climate conditions. An alternative that allows for early adaptation and complements the eventual changes that will be needed and reflected in codes and standards would be the introduction of a "Climate Change Adaptation Factor" (CCAF) into engineering practices. The "Climate Change Adaptation Factor" would ensure more timely and optimal adaptation of infrastructure and could incorporate two components, as needed. The first component would explicitly allow updating of existing climatic design values ($A_{current}$) while the second component would consider expected climate change ***increases*** in climatic design values ($A_{climate\ change}$) similar to adjustments proposed by the Association of British Insurers (2003).

Using a Climate Change Adaptation Factor, the user could undertake a risk assessment to determine whether to apply this Factor to design requirements, given that components are tabulated for geographical areas and include different climate model scenarios. For example, the factor could be applied when updated design values are needed and/or when the risks to specific infrastructure from climate change are likely to increase over time. While this approach has the advantage of being relatively easy to update as new climate data and climate change scenario information become available, it could have the disadvantage of being difficult for users and inspection personnel to understand initially and could carry the risk of being ignored unless backed by legislative or other authoritative action.

4. Premature Weathering of Infrastructure

In contrast to extreme events where the damage is done in minutes or days, premature failure caused by weathering or deterioration from the weather elements usually takes months or years to become evident. Similar to the natural environment, man-made structures are also subject to erosion caused by the slower day-to-day processes of wind-driven rain, by freeze-thaw cycles, frost depth penetration, wetting and drying, by abrasive materials, by the action of broad spectrum solar radiation and ultraviolet (UV) radiation, and by chemical breakdown in the presence of water, oxygen and assorted pollutants.

Buildings, for example, are particularly vulnerable to weathering impacts that compromise their durability and resilience to extremes over time. Uncontrolled moisture accumulation in structural materials can reduce the structural integrity of building components through mechanical, chemical and biological degradation. It is the function of the building envelope, which includes the exterior walls, foundations, roof, windows, insulation, connectors, and doors that enclose the indoor environment, to separate the indoor from the outdoor environments (Bomberg and Brown, 1993). To maintain its durability over time, the building envelope needs to prevent weather elements from entering the structure and becoming trapped inside the walls, which can cause wall components to continue to decay. Durability of the building envelope and provision of the desired service life more or less assures protection of building occupants from all weather elements and systems contained within it, along with the contents. If the building envelope fails during a storm, damage to contents typically raises the total loss by a factor of 2 to 9 over the cost of repairing the building itself (Sparks et al, 1994). Following Hurricane Andrew in August 1992, for example, building codes in the two counties affected in the Miami area were changed to require the building envelope to remain in place and capable of protecting contents during the design extreme wind event (Minor, 1994). Other publicized cases of moisture damages from envelope failures in North America include the Vancouver condos, North Carolina housing units, and Seattle leaky homes. Another study by the Norwegian Building Research Institute estimates that three-quarters of all building damages registered in Norway resulted from water and moisture infiltration and the health costs associated with problems from moulds, etc (Liso, 2001). These results, in effect, impose a requirement for durability over the service life of the building, where any loss of function over the service life of a structure may result in health costs (e.g. moulds) as well as infrastructure no longer able to resist extreme events.

Exacerbating concerns over the premature deterioration of infrastructure are issues related to aging and overextended infrastructure. Spending on public infrastructure has been declining steadily, when rated as a share of economic activity (IPCC, 2001a). In North America, for example, public spending on a broad range of new infrastructure projects represented almost 3.5% of GDP in the early 1960s, but had declined to less than 2% in the 1990s (Statistics Canada, 1999; USBEA, 1999). This reduced rate of spending on replacement and expansion of infrastructure to meet growing population and urbanization demands has resulted in a significant proportion of aging, “overextended” infrastructure that is increasingly vulnerable to selected climatic hazards (IPCC, 2001a). The American Society of Civil Engineers, for example, has warned that many dams in the United States have exceeded their intended lifespans (Plate and Duckstein, 1998). More than 9,000 regulated dams have been identified as being at high risk of failing, with the result that there may be significant loss of life and property from future failures.

Premature weathering or deterioration of structural materials is becoming a growing concern in many regions, perhaps related to the changing physical and chemical atmosphere. For example, in parts of North America, concerns are growing over the premature deterioration of materials such as clay bricks, reinforced concrete and pavement (Auld, 1999; Haas et al, 1999). In northern latitudes, there is evidence that recent warmer winters in traditionally colder winter climates are resulting in more frequent freeze-thaw cycles, leading to potentially greater weathering of infrastructure materials such as concrete and pavement (Auld, 1999; Stutzman, 1999; Green et al, 2003). Increasing freeze-thaw cycles in cold regions are also under suspicion for enhancing susceptibility to building roof ice damming and moisture damages

(Magnuson et al, 2000; Baker, 1967). If this rate of deterioration of infrastructure is not slowed through adaptation actions, existing structures may become more vulnerable to the changing climate of the future.

5. Adaptation Options and Actions Supporting Infrastructure

Because infrastructure built in current times is intended to survive for decades to come, it is critically important that adaptation options to climate change be developed today and implemented as soon as possible. In many cases, it is likely that the impacts of future climate change will lie outside of existing experience and coping ranges of infrastructure and adaptation options will need to be developed over time through "adaptation learning" and more effective pre-disaster planning. As much as possible, it is important that adaptation lessons be learned from current practices, with continuing emphasis on the need for post-storm forensic studies and learning from failures.

The many implications of the changing climate will require a structured approach for the reinforcement and retrofit of existing infrastructure, planning for redundancy of critical infrastructure and the updating of infrastructure codes and standards. Underlying these activities will be an ongoing need for careful monitoring of regional climate conditions and prioritization of adaptation actions, as described below.

Infrastructure adaptation actions needed to help communities and decision-makers cope with the changing climate include:

(i) Updated and Regularly Revised Structural Codes and Standards, Climatic Design Values and Engineering Practices (Section 6)

- Update codes and standards and their climatic design values, according to the following requirements:
  - Address deficiencies and uncertainties in existing climatic design values;
  - Regularly assess and update climatic design values;
  - Consider changing safety factors (or other measures) to reflect growing uncertainties and risks under climate change;
  - Develop analytical techniques to incorporate climate change and socio-economic scenarios into climatic design values.
- Incorporate Climate Change Adaptation Factors for immediate updated adaptation requirements
- Ensure sufficient density, data quality and record length of climate networks
- Enforce compliance to infrastructure codes and standards
- Assess engineering practices in light of the changing climate
- Reduce premature deterioration rates for infrastructure

(ii) Prioritized Adaptation Actions for Critical Infrastructure and Vulnerable Regions (Section 7)

- Prioritize and develop adaptation options for the most critical infrastructure
- Prioritize and develop adaptation options for the most critical regions
- Incorporate infrastructure adaptation into the planning cycle

(iii) Enhanced Community Disaster Management (Section 8)

- Provide accurate early Weather Warnings of hazards
- Phase in avoidance of vulnerable regions
- Encourage energy efficiency and self-sufficiency
- Support multi-disciplinary forensic studies (adaptation learning) and risk reduction learning
- Require community pre-disaster and post-disaster management planning (through regulation).

(iv) Education and Outreach of Engineering and Planning Communities and Public (Section 9)

- Create awareness of community risks and vulnerabilities
- Encourage closer collaboration between planning and engineering communities and climate community
- Include topics of disaster resistant construction and climate change adaptation in curriculum for engineering and planning professions.

6. Structural Codes and Standards, Climatic Design Values and Engineering Practices

"No regrets" adaptation options are available in the here and now that can reduce the vulnerability of infrastructure to existing climate variability and help with future climate change. In Canada, and likely elsewhere in the world, current long-standing gaps and deficiencies in the determination of climatic design values prevent optimum decisions from being made on infrastructure reliability and safety. Structures designed using climatic design values that are based on poor climatic data, sparse data or previously short dataset records are particularly vulnerable. It is important that such uncertainties and deficiencies in climatic design values be addressed on a priority basis to ensure effective adaptation to current climate variability. A better understanding of these uncertainties is needed to determine whether and by how much structures can tolerate slight increases in loads. For example, the climatic design values used in any given building code or infrastructure standard vary considerably by locality and region, by the date of its calculation and on whether design values have been regularly updated. The uncertainties in climatic design values will depend strongly on the complexity of the climate in a locality, the density of climate stations, quality and length of the climate data used for the estimation of climatic design values, the frequency of the extreme climate event, statistical approaches used and spatial and temporal interpolation approaches applied for estimation at a location (Canadian Commission on Building and Fire Codes, 1995). In the near future, it will become even more important that climate station record lengths and quality be enhanced or at least maintained to allow adequate calculation and interpolation of climatic design values and that climate networks be enhanced or maintained in areas of sizable populations, near critical infrastructure and in the regions most vulnerable to climate change.

The impact of uncertainties in the estimation of historical climatic design values need to be understood and reduced in order to update and optimize the safety and economy of future climatic design values. For example, conservative assumptions that were applied regionally in past can result in additional “margins of safety” or over-design in existing climatic design values. In other cases, due to climate data shortfalls not considered in data treatments or due to regional trends towards increasing climate loads, some existing climatic design values may already be at risk under current climate conditions and not be able to accommodate any further increases in loads.

Once the uncertainties in existing climatic design values are minimized, it is important that climatic design values be regularly updated over time. Where adaptation urgency is important and codes and standards cannot be changed soon enough, a Climate Change Adaptation Factor may need to be applied. Climatic design values for codes and standards need to reflect the changing climate conditions and be assessed against regional climate trends to determine whether existing “margins of safety” have any remaining tolerance to accommodate increases in loadings. Localities and regions where climate trends are encroaching on tolerance limits require, on a priority basis, increases in climatic design values for new structures and potential structural reinforcement for existing “at risk” structures.

Methodologies are needed that allow climate change scenario information to be incorporated into design of infrastructure. Such studies and methodologies are rare. A study by the Meteorological Service of Canada, for example, on the potentially changing risks of severe ice storms has shown that several complementary analyses should always be considered when projecting the implications of extreme weather under changing climate conditions (Klaassen et al, 2003a; Cheng et al, 2004). The study, which identified regions of increasing risks under initial winter warming, indicated that considerable potential exists for the use of statistical synoptic map typing procedures in identifying trends in large scale or synoptic, regional and local scale weather patterns for severe ice storms. Statistical map typing methodologies also have considerable potential as a technique to downscale projections from global and regional climate models using fields more reliably handled by the global climate models. Other complementary analyses used in the study (Klaassen et al, 2003a) included storm tracking, assessment of threshold synoptic storm components for the most extreme ice storms affecting eastern North America, assessment of climate impact thresholds, and spatial or analogue approaches that correlate conditions and impacts in adjacent regions during the most severe storms.

Existing infrastructure failures are often shown to result from inadequate compliance to codes and standards. As a result, compliance and the development of institutional capacity to implement building standards and codes of practice will become increasingly important in future. Several studies have documented widespread damages as a result of the construction industry not complying and building inspections not detecting the violations. For example, the hurricane that hit Northwest Norway in 1992 caused damage to buildings in the order of NOK $1.3 billion, with total damages to structures in general amounting to approximately NOK $2 billion (Liso et al, 2003). The bulk of the damage to buildings was incurred on roofs and roofing and could have been avoided had the existing Building Regulations and Codes of Practice been followed (Liso et al, 2003). In the UK, analysis of claims and weather data have shown that a large percentage of wind-related damage takes place at wind speeds lower than those to which buildings are nominally designed and are caused by failures to apply existing codes of practice (Buller, 1993).

Because of the varying safety factors used for each type of infrastructure, it is theoretically possible that some structures designed for longer return period extremes, such as hospitals, may be able to withstand more extreme atmospheric hazards with much longer return periods while others structures with minimal safety factors, such as electrical distribution lines, may readily encroach on the limits of their load tolerances. Where existing safety factors are relatively high or conservative, adaptation actions may not be required immediately to ensure structural safety. In other cases, a Climate Change Adaptation Factor may be needed to ensure timely adaptation actions. Further study is needed to determine whether and when structures will become vulnerable to the increasing uncertainty of climate design values and to assess the impact of changing engineering practices and codes and standards on the ability of structures to withstand surprises in extreme weather loads. In prioritizing adaptation requirements, studies are needed to identify which types of structures are most vulnerable to the impacts of climate change (e.g. electrical distribution lines, sewers). Such studies will also help to determine to what extent tendencies towards standardized cost-effective structures today may have compromised robustness or adaptability of structures. Alternatively, a review of generic building typologies that have survived over centuries may reveal characteristics that make these structures particularly adaptable to climate variations and changes (Steemers, 2003b). The learning from such a review would serve to highlight adaptative attributes and sound building practices that historically may have been better adapted for local climatic conditions and also reveal current practices that are contrary to effective adaptation.

Finally, the relationship between atmospheric weathering processes, building materials, maintenance schedules and structures is complex and in need of further study. The understanding of how degradation and damage can best be reduced economically is of growing importance for the design and construction of structures. In many areas, future building materials, structures and building enclosures, will need to withstand greater climatic impacts than they do today. When designing building enclosures to resist wind actions, materials and engineering practices will need to ensure the integrity of the envelope so that moisture does not enter the structure (Holm, 2003). A particular challenge will be the identification of weathering processes of greatest importance in order to develop appropriate adaptation responses. For instance, the duration of excessive precipitation may prove of greater importance for certain types of building facades, while the intensity of driving rain may be the most important element for other types of external walls. Freezing and thawing cycles may prove significant in winter climates for performance of masonry and concrete construction while polymer materials may be more affected by the sum of ultraviolet radiation (Holm, 2003). Adaptation actions could take the form of different formulations for materials (e.g. concrete, clay brick) or different engineering practices to ensure greater durability and requirements in standards for preventative maintenance.

7. Prioritize Adaptation Actions for Critical Infrastructure and Vulnerable Regions

Critical infrastructure is defined in Canada as “those physical and information technology facilities, networks, and assets whose disruption or destruction would have serious impact on the health, safety, security, and economic well-being of Canadians or on the effective functioning of governments in Canada” (Grenier, 2001). Enhanced design of the most critical infrastructure (such as communications structures, power supply and distribution systems and emergency shelters) and built-in redundancies may improve the likelihood of continuous operation during extreme weather events, as well as improve response and recovery following disasters and generally reduce the vulnerabilities to regionally increasing extremes. The survival or failure of housing has also been claimed to be a key factor determining the severity of a natural disaster and the ability of a community to recover, indicating the importance of proper design and construction of housing (Davenport, 1999).

Although the damages from the eastern North American Ice Storm of January 1998 were initiated by a particularly severe ice storm, the event quickly turned into a technological disaster because of cascading impacts from power outages. Due to a whole chain of events, affected communities experienced a major malfunction of some of their other most critical infrastructures such as telecommunications, transportation, banking and financial systems, drinking-water supplies and, of course, energy infrastructures. The January 1998 Ice Storm emphasized that all components of critical infrastructure are inter-linked today, particularly given the nature of today’s electronic and “just-in-time delivery” economies, industries and communities.

While particular types of infrastructure will require priority adaptation action, particular regions may also require priority adaptation actions for enhanced design of new infrastructure and protection of existing infrastructure. Some of the greatest impacts of climate change on infrastructure will likely be noticed in exposed coastal zones, flood plain regions, heavily urbanized areas and permafrost regions. Adaptation options will require a suite of actions ranging from avoidance of the most vulnerable sites to expensive protection structures.

Melting of permafrost in northern regions will require expensive monitoring of buildings, road-beds, pipelines, utility lines, dams and water diversion channels. The net result likely will be extensive repairs and modifications of existing structures, and changed techniques for new construction. While tested adaptation solutions are available, given warning of changes, reliable local information, and funding, the costs will be expensive. Proven methods of supporting roads, airports, and buildings can prevent settlement under permafrost thawing while expensive maintenance can protect facilities built on permafrost (University of Alaska Anchorage, 2000). New structures in permafrost regions can be built over gravelly “thaw-stable” permafrost to avoid the worst consequences, but more costly up-front actions will be required to select the most reliable and least vulnerable sites as the permafrost thaws.

Many structures and communities in coastal zones and flood plains will face significant risks from the changing climate as a result of sea level rise, increases in storm surges, increases in water and air temperature, more extreme rainfall and storm intensity, and resulting land erosion and inundation from the sea. These impacts will likely lead to increased susceptibility of buildings and structures to damages in vulnerable locations and to more frequent disruptions to services (Planning Institute of Australia, 2004). All of these impacts could affect the future design and location of development. The more risky coastal locations that contain high cultural, environmental or financial value may require construction of expensive structures for protection against inundation, such as barriers and dykes and reinforcement of buildings and other infrastructure, along with measures to reduce premature weathering of materials, including enhanced maintenance.

It is expected that climate change will affect the costs and timelines for planning, upgrading and maintaining infrastructure. Prioritization of required adaptation and mitigation actions will need to account for the variable lifecycles of structures and replacement cycles, including infrastructure maintenance and upgrade cycles. Table 1 indicates the expected lifecycle activities for the various types of infrastructure. As the Table indicates, planning decisions are being made about buildings and other infrastructure today that have a very high probability of being affected by the direct impacts of climate change in the future.

The design life of a structure becomes important in determining what climate change impacts can be expected over its lifetime. On the adaptation side, structures with a design life of 30 to 50 years will need to consider different future climate conditions than others with a longer design life of 100 years. Short-lived assets and components, such as heating, ventilation and cooling systems, tend to be replaced at various times during the lifespan of a building, offering opportunities for adaptation or “phasing in” of systems to the changing climate. Other medium-life assets such as industrial plants, oil and gas pipelines, and conventional power stations that need to be modernized to take advantage of competitive technologies are also likely to be replaced or relocated over shorter time scales than other infrastructure and can become adaptable, particularly through upgrades and relocation. For structures not as likely to be relocated or replaced, such as housing, the challenges of adapting basic structural components will be more difficult. Due the varied ages and replacement life of structures in the built environment, it will take time to change structures, institutions and other policies to cope with climate change realities.

The changing climate will, in effect, shorten the lifespan of existing structures in many regions. Where extremes increase, the impact will be a reduction in the "effective" return period event that existing structures were built to withstand. For example, Kharin and Zwiers (2000) analyzed changes in daily precipitation extremes under climate change using output from an ensemble of transient climate model simulations and concluded that the return period of extreme rainfall events may, on average, be reduced by a factor of two. This means that, under a changed climate, a current 20-year rainfall event could occur every 10 years. As the effective return periods of extreme events change with the climate, weather extremes will tend to exceed the design specifications for structures more frequently, decreasing the

Table 1. Infrastructure Lifecycle Timeframes (Adapted from Planning Institute of Australia, 2004)

STRUCTURE	PHASE	TYPICAL EXPECTED LIFECYCLE
Commercial Buildings	Retrofit Demolition	20 years 50-100 years
Housing	Additions and Alterations Demolition	15-20 years 60-100 years
Roads	Maintenance Resurface Reconstruction/Major Upgrade	Yearly 5-10 years 20-30 years
Bridges	Maintenance Resurface concrete Reconstruction/Major Upgrade	Yearly 20-25 years 60-100 years
Rail	Major refurbishment Reconstruction/Major Upgrade	10-20 years 50-100 years
Airports	Major refurbishment Reconstruction/Major Upgrade	10-20 years 50 years
Seaports	Major refurbishment Reconstruction/Major Upgrade	10-20 years 50-100 years
Dams/Water Supply	Major refurbishment Reconstruction/Major Upgrade	20-30 years 50 years
Waste Management	Upgrade Major Refurbishment	5-10 years 20-30 years
Sewers	Reconstruction/Major Upgrade	50 years

durability and resilience of the structure. Repeated extreme event loads (fatigue loads) cause deterioration of materials and can lead to eventual failure of the structure.
In the timeframe of climate change impacts, it is evident that new infrastructure will play an increasingly important role in building adaptive capacity as older structures are replaced over time. For example, within the next 50 years and assuming a replacement rate of 1% to 1.5% for buildings, it is likely that roughly half of existing buildings will need to be demolished and replaced (Fernandez, 2002). Hence, within the timeframes for climate change impacts, new buildings will accumulatively account for an equal or greater fraction of the building stock and need to be designed to enable adaptation to climate change as soon as possible (e.g. through continuously updated building codes, increased safety factors and incorporation of climate change scenarios).

The adoption of practices supporting the “diversified lifetime” of a building may also become a powerful adaptation option (Steemers, 2003a). This will require that buildings and other structures become “designed for disassembly, separation technologies, materials reclamation and recycling, loose-fit detailing, lightly-treading foundations and other technologies that allow use to change over time” (Fernandez, 2002). The concept behind the “diversified lifetime” is that a structure be designed using a number of different parts with different design lives. As a result, uncertainty about a building’s long-term use or environmental conditions can be reflected by reduced investment in some of its construction or components, with an inherent potential to adapt spatially and functionally to change. In the case of climate change, the objective would be to anticipate changing climate conditions (or even market conditions) and where there is certainty, to consider whether it is worth investing for the longer term. For the buildings sector, this could involve investing in a strategy for the key long-term parts of the building that will need to be able to cope with predicted climate change and allowing the short-term components of the buildings or structure to be designed for minimal climatic change and maximum flexibility.

8. Improved Community Disaster Management

Concerns over the impacts of weather-related hazards on vulnerable populations are growing, due to increasing risk factors such as population growth and urbanization, a rising proportion of poor living in vulnerable locations and the changing climate. Actions to reduce exposure to weather hazards or disaster management are necessary and will need to include adaptation actions such as planned responses to timely and accurate weather warnings, proper land use planning, good engineering design and practice, good maintenance of structures and efficiency and self-sufficiency in use of energy and services (Freeman et al, 2002; Planning Institute of Australia, 2004).

A very critical part of a disaster management strategy is the completion of a Vulnerability or Risk Assessment. Vulnerability is defined as:

“The extent to which a community, structure, service, or geographic area is likely to be damaged

or disrupted by the impact of a particular disaster hazard, on account of their nature, construction, and proximity to hazardous terrain or a disaster prone area." (ADPC 2000).

Vulnerability assessments identify sources of hazards, vulnerable groups, likely risks and potential interventions. For example, vulnerability assessments identify weather and other types of hazards, identify critical infrastructure at risk to these weather hazards along with vulnerable groups and then develop potential adaptation and prevention interventions. As illustration, the province of Ontario, Canada, recently passed its Emergency Management Act (Government of Ontario, 2003) mandating that all municipal and regional governments adopt disaster management planning. The legislation requires that municipalities identify and assess the various hazards and risks to public safety that could give rise to emergencies in their communities and develop a prioritized emergency response plan, including the identification of infrastructure at risk. The Act also requires that municipalities develop comprehensive plans to reduce and prioritize risks, including development of a municipal disaster mitigation strategy, planning for high risk events, development of an emergency recovery plan, implementation of guidelines for risk-based land use planning and development of public education programs (Government of Ontario 2003). In support of these measures, the Meteorological Service of Canada (Auld and MacIver, 2004; Meteorological Service of Canada, 2004) recently released a web site and publication on atmospheric hazards that allows emergency managers to access climatological hazards information, customize atmospheric maps for their localities and to overlay regional combinations of hazards maps.

The successful application of early warnings is another effective measure for disaster reduction. Effective warnings of impending events allow people to take actions that save lives, reduce damage, reduce human suffering, and speed recovery. In essence, accurate and timely weather warnings play a critical role in buying the time needed to evacuate populations, reinforce infrastructure and prepare for emergency response. While scientists and emergency managers are improving capabilities to warn for more weather and related environmental hazards and to increase warning accuracy, greater improvements are needed in measures to deliver warnings in a timely manner and to those people and regions mainly at risk. Improvements are also required for better coordination among warning providers, for better education of those at risk, and in building partnerships among the many public and private groups involved in response.

In many countries, weather warning systems consist of an escalating series of messages intended to alert the public and emergency responders to impending weather hazards of various magnitudes. Typically, these warning systems consist of advisories or watches for potential hazardous weather, with warnings issued as hazardous weather becomes more certain. As risks increase regionally under climate change, improved and expanded weather warning programs, such as specialized warnings for emergency responders, may be needed along with increased lead time. For example, the U.K. Meteorological Office currently provides Early Warnings of potentially disastrous weather events to emergency responders up to five days in advance so they can be prepared to respond to the effects of high impact weather. Because prediction of severe weather at this range, especially in any detail, is difficult, these Early Warnings are expressed in terms of probabilities, with warnings issued when the probability of disruption due to severe weather somewhere in the UK is 60% or more (U.K. Meteorological Office, 2004). Other expanded weather warning programs could include escalated warnings of potential community disasters that are based on infrastructure damage thresholds, as discussed in Section 3. These weather-infrastructure warnings could include warnings of extreme ice loads or wind loads with the potential to disrupt transportation and to cause widespread failure of electrical power distribution networks (Cheng et al, 2004) or alerts of extreme snow loads giving increased risks for building collapses (DeGaetano and Wilks, 1999). Similarly, expanded weather-health warnings and response systems for potentially "dangerous" environmental conditions could include community Heat Alert systems for vulnerable populations, waterborne disease outbreak and beach water quality alert systems for water managers (Auld et al, 2004) as well as other health emergency alert systems. The Meteorological Services of several countries, including Canada, currently provide Heat Alert prediction systems for selected pilot cities when risks of elevated mortalities from heat wave events reach regional threshold levels. The U.K. Meteorological Office also supports health-related weather services aimed at assisting in more effective public healthcare planning and delivery. By building high-quality weather information into the decision-making process, public health officials, healthcare providers, researchers and others are able to plan emergency health care operations and activities with greater confidence, manage workload more effectively and make the best use of limited healthcare resources (UK Meteorological Office, 2004). While emergency disaster response is important, climate change adaptation options for infrastructure and communities will ultimately require more intervention by land use planning authorities.

Land-use planning is a powerful tool to help reduce the loss of life and property. One study that indirectly illustrates this concept compared impacts from flooding storm events in Michigan and neighbouring Ontario (Brown et al., 1997) and found that nonagricultural flood damage from a set of storms moving through Michigan exceeded that of southwestern Ontario by a factor of about 900, even though the flood yields in Ontario were greater than those in Michigan. Their analysis ascribed the cause as greater development in flood-prone areas in Michigan. The storms generally exceeded land-use design thresholds in Michigan, whereas in Ontario they did not.

Many of the following disaster management planning measures will need to be considered in future to better deal with the increasing risks to communities (Planning Institute of Australia 2004), but will not likely be "welcomed". These measures include:

- More intensive and efficient use of land in areas less exposed to climate change risks. This may mean encouraging greater urban consolidation and avoiding development in high-risk areas (e.g. flood plains and coastal zones subject to sea level rise and storm surges);

- Locating new development in areas not vulnerable to the impacts of climate;

- Planned retreat or a focus on systematic abandonment of land, ecosystems and structures in vulnerable areas;
- Identification of high risk areas of high cultural, environmental, strategic or financial value for consideration of adaptation options such as constructing works to protect against sea level rise and flooding events;

- Enhanced building design for continued occupation of vulnerable regions (e.g. exposed coastal zones and flood plains).

Forensic disaster investigations likely will become increasingly important for adaptation learning. The performance of structures during extreme events needs to be monitored to confirm and to further fine-tune engineering design practices, as well as to assess climatic design values. As an example, many lessons were learned from the detailed investigations of how structures responded to the Barrie and Grand Valley tornadoes in southern Ontario, Canada in 1985. The studies of damages following the tornado outbreak indicated that occupants of houses that were destroyed by the tornadoes survived in buildings when the walls of their homes were properly secured to the foundations (Allen, 1986). As a result of these and other studies, the 1995 National Building Code of Canada increased requirements for anchoring of walls to foundations for tornado prone areas (Canadian Commission on Building and Fire Codes, 1995). Similar adaptation lessons have been learned worldwide from forensic investigations of damages following hurricane landfalls and flooding events. As illustration, the massive destruction of Hurricane Andrew ($26 to 30 Billion), which struck the southeastern US in 1992, brought issues of construction, mitigation and the insurance industry into sharp focus (International Hurricane Centre, 1999). The recommendations from the Committee that investigated the damages had an impact on the South Florida Building Code and construction regulations. Changes were introduced for new product approval test criteria for building components that included impact and fatigue tests able to simulate flying debris. The Committee also determined that the most significant hurricane damages resulted from the loss of "integrity of the building envelope" and that the breaching of the exterior of a structure set off a chain of events that led to more severe damage (e.g. shutters can significantly reduce the net damage that a building sustains in a hurricane).

Forensic investigations of flooding events often yield valuable insights. For example, the Meteorological Service of Canada, in partnership with the province of Ontario, several regional watershed management Conservation Authorities and the Ontario Flood Forecasting and Warning Committee, undertook a series of forensic studies of seven high impact rainfall storms and flooding events in Ontario, Canada for the year 2000. From these studies (Klaassen et al, 2003b), several adaptation recommendations were jointly developed by all of the study partners and have widespread applicability for government jurisdictions, decision-makers, meteorological services and planners. Some of these adaptation recommendations to reduce risks from flooding events included:

- Regular forensic reporting and studies are beneficial to the public and yield valuable adaptation lessons. The studies need to include an assessment of the meteorology, technology, weather prediction and warning improvements, impacts, historical climatological conditions, climatic design information and engineering requirements and be undertaken by multi-disciplinary teams.

- For heavy rainfall events, weather warnings and their threshold criteria need to consider antecedent or accumulated rainfall conditions.

- The quality and amount of weather and climate data are critical for the detection and warning of an extreme rainfall event and for determination of updated engineering design values.

- Coordinated efforts are needed to ensure that data networks remain sufficiently dense to capture events, provide guidance for early and accurate weather warnings, allow for updating of climatic design information and assist improvements to weather radar and other forecasting tools.

Adaptation measures that decrease the energy requirements of buildings and ensure more disaster-resistant energy service systems (e.g. renewable sources) can reduce losses from business interruptions and damages to property, while helping to mitigate increases in the greenhouse gases driving climate change. For example, energy efficient buildings are of value when backup power systems are needed during times of power outages. In the North American ice storm of 1998, the costs of perished foods in residential freezers lost as a result of power outages was one of the larger costs faced by homeowner insurers. Likewise, more energy efficient windows, including those with retrofit films, can reduce energy losses by half while increasing their resistance to breakage from flying debris in windstorms. Studies, for example, have indicated that double-glazed windows with one low e-coating take three to four times longer to break than ordinary double-glazed windows (Anderberg, 1985; Mills, 2003). Similarly, some improved building envelopes (i.e. insulated concrete form construction) tend to be more resistant to flying debris than standard timberframe construction (Farnsworth, 2000). Insulating water pipes or insulating cold spaces where water pipes run can also save energy and reduce risks of frozen water pipes and water damage since insulated pipes cool and freeze less readily. The US insurance industry estimates that claims from frozen pipes have cost US$4.2 Billion over 10 years (IBHS and SBA, 1999).

9. Education and Outreach of Engineering and Planning Communities and Public

The implementation of cost effective climate change adaptation measures to protect communities will require greater knowledge and understanding of climate change impacts in the public and private sectors. In particular, the planning and engineering communities will need to work closely with the climate community in order to become knowledgeable on regional climate change impacts for infrastructure and to identify and implement regional adaptation options. Consequently, an important step in promoting safe building construction in vulnerable regions will be the requirement to create awareness and appreciation of levels of risks within communities and within relevant professions. Since planning is a future oriented profession, adaptation to climate change is a challenge that this profession must accept and act upon as soon as possible. At the same time, professionals coming out of engineering and architectural programs as well as practicing professionals will need to have greater exposure in their curriculum to disaster resistant construction and awareness of climate change impacts and the need for adaptation.

10. Conclusions

Climate change will impact infrastructure through gradual changes in weather patterns and increasing vulnerability to extreme events. Because infrastructure built in current times is intended to survive for decades to come, it is critically important that climate change adaptation options be developed today and implemented as soon as possible. The many implications of the changing climate will require a structured approach for the updating of climate design values, codes and infrastructure standards, for reinforcement and retrofit of existing infrastructure and for planning redundancy of critical infrastructure. Underlying these activities will be an ongoing need for careful monitoring of regional climate conditions and prioritization of adaptation actions.

The first important step in reducing risks to infrastructure is to seek to identify gaps in current capacity for addressing climate variability and extremes. “No regrets” adaptation actions are available in the here and now to reduce the vulnerability of infrastructure. These “no regrets” actions include measures such to reduce uncertainties in climatic design values and to update calculations, enforcement of engineering codes and standards, safeguarding the quality and length of climate data records and networks, regular maintenance of existing infrastructure, consistent forensic analyses of infrastructure failures and community disaster management planning. In other cases, it is likely that the impacts of future climate change will lie outside of existing experience and coping ranges of infrastructure, requiring that adaptation options be developed over time through “adaptation learning”.

In all cases, adaptation to climate change will require that planners, their agencies, the engineering community and community decision-makers consider timeframes beyond statutory requirements and even beyond the lifetime of most individuals. Improved understanding of climate change impacts and the need for adaptation must be combined with better risk assessment of community climate change impacts and vulnerability, the identification and avoidance of development in vulnerable areas and ongoing incorporation of adaptation strategies into land use planning and community disaster management planning. In essence, adaptation options for infrastructure will require “tough” actions such as the location of new development in areas less vulnerable to the changing climate, the abandonment of land, structures and ecosystems in vulnerable areas, location of greenbelts in residential areas, altered building design and retrofits of existing structures and defence of vulnerable areas. Such actions will entail significant costs, disruptions to communities and require political commitment and cooperation between all levels of government.

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