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INCORPORATING CLIMATE CHANGE CONSIDERATIONS INTO FLOOD MAPPING AND INFRASTRUCTURE DESIGN IN NEWFOUNDLAND AND LABRADOR

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Abstract: Climate change is projected to bring warmer, wetter and more extreme events across Newfoundland and Labrador (NL). The potential for infrastructure damage and associated public safety risks, e.g. coastal erosion and property damage, will vary across the province. Recent climate trends and future climate projections show that past weather conditions can no longer be used to accurately predict the future and accurately assess risk. The Government of NL (GNL) has a suite of world class data and resources available for this purpose, however a number of issues has limited awareness and deployment of these resources, including the fact that key decision-makers and professionals are either unaware of the resources or lack in-house expertise to use them. Memorial University of Newfoundland has partnered with the GNL, Municipalities Newfoundland and Labrador, Professional Engineers and Geoscientists Newfoundland and Labrador, and Engineers Canada on a project funded through Natural Resources Canada's BRACE program to train professional engineers and planners on how to incorporate climate change considerations into infrastructure planning and design. We will discuss existing tools developed by the GNL, and how they have been used to date for flood mapping and infrastructure design, and plans to increase the use of these tools. We will briefly describe some recent efforts in knowledge transfer and training of professional engineers in the use of these tools. Finally, we discuss efforts underway for further tool development and to identify important knowledge gaps that limit our ability to incorporate climate change into infrastructure planning and design.

1 INTRODUCTION

Climate change is projected to bring warmer, wetter and more extreme weather conditions across Newfoundland and Labrador (NL), with the most significant impacts expected for residents of Labrador. Extreme precipitation and coastal storm events are expected to increase in both frequency and intensity, and there is a growing number of climatologists that believe current climate change projections underestimate impacts. The degree of change will vary across the wide-ranging geography and population distribution of the province, and therefore potential for infrastructure damage and associated public safety risks, e.g. coastal erosion and property damage, will vary in accordance. In March 2017, the Government of NL (GNL) announced a plan to invest $3 billion dollars over 5 years through its infrastructure plan. Design of infrastructure requires the use of the statistics of extreme events to balance the cost of construction with estimates of the risk of failure. Recent climate trends and future climate projections show that past weather conditions can no longer be used as a reasonable proxy for future conditions, or to accurately assess risk over the life many infrastructure projects. At present, climate change, or non-stationarity, is not consistently incorporated into infrastructure design in NL. Integrating climate change considerations into infrastructure and development decisions increases the likelihood that new infrastructure investments will be able to withstand the climate of the future.

The GNL has a suite of world class data and resources available for this purpose, which includes recently updated (Finnis and Daraio 2018) regionally downscaled climate data for the province, and updated Intensity-Duration-Frequency curves derived from these data. In 2016, GNL commissioned an independent study on climate adaptation capacity, and examined the application of existing climate data and tools in decision-making processes. The study concluded that awareness and deployment of these resources is low, which has been attributed to a number of limitations. Key decision-makers and professionals are either unaware of the resources or lack in-house expertise to use them. For example, small municipalities either did not know that including climate change should be made explicit in RFPs or assumed that climate change would be considered by engineering consultants even if it was not explicitly referenced. At the same time, engineering consultants, working to ensure their bids were cost competitive, did not necessarily incorporate climate considerations if not requested. Further, consultants stated that municipal regulations and oversight are inconsistent. To better integrate climate change into engineering and planning decisions, the study recommended developing technical training and awareness workshops that apply climate adaptation tools and resources tailored to the region’s needs, as well as supporting policy developments that better integrate the application of these tools and resources in tender requirements.

Memorial University of Newfoundland has partnered with the GNL, Municipalities Newfoundland and Labrador (MNL), Professional Engineers and Geoscientists Newfoundland and Labrador (PEGNL), and Engineers Canada on a project funded by Natural Resources Canada (NRCan) to train professional engineers and planners on how to incorporate climate change considerations into infrastructure planning and design. In this paper, we will (1) provide an overview of the climate change projections that are available for NL, and (2) discuss existing tools developed by the GNL incorporating climate change projections including updated precipitation intensity-duration-frequency (IDF) curves and flood risk mapping. We will also briefly discuss (3) the coastal monitoring program for NL, and (4) describe some of our recent efforts in knowledge transfer and training of professional engineers in the use of these tools. Finally, we (5) describe areas of continuing research to fill in and identify some important knowledge gaps limiting our ability to incorporate climate change into infrastructure planning and design.

2 CLIMATE CHANGE PROJECTIONS

Finnis and Daraio (2018; CPR2018) recently updated a 2013 report by Finnis (CPR13) on climate projections for the province of Newfoundland and Labrador. CPR13 used data from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009) for 21st-century projections from an ensemble of dynamically downscaled interpretations of CMIP3. Since CPR13, a number of new datasets and analysis tools have been developed for the purposes of regional/local scale climate, including the CMIP5 multi-model ensemble, and updated greenhouse gas emissions scenarios. There have also been significant advances in bias correction techniques and the projection of extreme events. Together, these advances provided an opportunity to better explore likely regional/local scale climate impacts and quantify associated uncertainty in CPR2018.

CPR2018 explores a wider range of climate projections than did CPR13 and requires fewer assumptions regarding statistical distributions of relevant climate variables. The most significant improvement is the inclusion of new statistically downscaled climate projections, produced by establishing statistical relationships between GCM output and a high-resolution climatology covering North America. By contrast, CPR13 used exclusively dynamically downscaled projections, produced by driving a high-resolution RCM with lower resolution GCM output. Both approaches have strengths and weaknesses (e.g. Wilby and Wigley 1997), and are widely used. Dynamic downscaling is grounded in current understanding of physical processes; this means all results are physically consistent. It’s important to note that the quality of the RCM results can be limited by biases in the GCM output driving them; while an RCM may be able to reduce some biases, they may preserve (or even amplify) others. There may also be concerns related to conservation laws (Roberts and Snelgrove 2015) and best modeling practices (e.g. Dai et al. 2010, Lo, Yang and Pielke

2008). Statistical downscaling is often less expensive to implement but requires assumptions regarding relationships between GCM output and the observed climate, and how these relationships change as climate shifts. This approach also requires reliable information about the current climate (e.g. from climate stations); this can be a problem over much of Canada, where available observations are often sparse. Using results from both downscaling approaches provides better quantification of likely climate outcomes and identification of robust features of projected change.

NARCCAP has now been superseded by the North American Coordinated Regional Climate Downscaling Experiment (NA-CORDEX; Giorgi 2015). Updates include: (i) the use of newer GCM and RCM versions, (ii) projections based on the CMIP5 suite of simulations, (iii) a handful of GCM/RCM combinations running at higher resolution (~25km rather than 50km; however, many combinations remain limited to ~50km), (iv) coverage of the full 21st century, and (v) the use of multiple greenhouse emissions scenarios. Results are based on Representative Concentration Pathways (RCP) emissions scenarios 4.5 and 8.5, where the numbers reflect the additional radiative forcing produced by the end of the century (Moss et al. 2010).

In addition to NA-CORDEX data, new data products from the Pacific Climate Impacts Consortium (PCIC) were examined. Rather than increasing resolution through the use of a regional model (dynamic downscaling), PCIC approached downscaling by establishing statistical relationships between GCM output and a high-resolution climatology covering North America (Hopkinson et al. 2011). This statistical downscaling was constructed using a hybrid of Bias Correction/Constructed Analogues (BCCA; Maurer et al. 2010) and quantile mapping, referred to as BCCAQ (Werner and Cannon 2015). PCIC offers daily data (minimum temperature, maximum temperature, and precipitation) at roughly 10km resolution, covering the full 1950-2101 period, based on simulations from twelve GCMs, forced with both RCP 4.5 and 8.5 scenarios.

Table 1: Projected climate indices available for Newfoundland and Labrador

Climate Index	Units	Calculation Type
Average Daily Mean Temperature	ºC	Average
Mean Daily Minimum Temperature	ºC	Average
Mean Daily Maximum Temperature	ºC	Average
Cooling Degree Day	Degree Day	Sum
Heating Degree Day	Degree Day	Sum
Growing Degree Day	Degree Day	Sum
Number of Frost Days	Days	Sum
Number of Frost Free Days	Days	Sum
Maximum Heat Wave Duration	Days	Maximum
Mean Daily Precipitation	mm	Average
Mean Intensity of Precipitation Events	mm/day	Average
90th Percentile of Precipitation Events	mm	Alternate
Maximum 3-day Precipitation	mm	Maximum
Maximum 5-day Precipitation	mm	Maximum
Maximum 10-day Precipitation	mm	Maximum
Number of Days With 10mm or More of Precipitation	Days	Sum
Maximum Number of Consecutive Dry Days	Days	Maximum
Average Dry Spell Length	Days	Average
Median Dry Spell Length	Days	Alternate
Standard Deviation of Dry Spell Length	Days	Alternate

Downscaled climate change projections for 20 climate indices (Table 1) are available in GIS format by request. A gridded domain shapefile was used as a base map, and tables containing values for all climate indices and the uncertainty measures can be joined to the base map for easy viewing (Figure 1). The locations of all precipitation gauges where IDF curves have been updated (see Section 3.1are also available in GIS format with links to the pdf versions of the IDF curves on the GNL website (https://www.exec.gov.nl.ca/exec/occ/climate-data/index.html).

3 EXISTING TOOLS

3.1 Climate Projections and Intensity-Duration-Frequency Curves

Station data (Figure 1) used to ground model projections was taken primarily from the Adjusted Homogenized Canadian Climate Data (AHCCD) archive (Mekis and Vincent 2011, Vincent et al. 2012), consisting of station data corrected for various instrumentation- and location-related sources of error. In some cases, this has been supplemented by daily precipitation and temperature data taken directly from Environment and Climate Change Canada’s Historical Climate Data Archive; this is the uncorrected station data that informs the AHCCD archive. Using the uncorrected daily station data may produce some errors related to instrument error, station movement, or changes in standardized equipment; however, it was necessary to use these to get projections for all stations examined in CPR13 and the 2015 provincial IDF update (Conestoga-Rovers and Associates 2015). Data quality concerns are balanced by the benefits associated with increased spatial coverage and compatibility across Government of Newfoundland and Labrador climate documents. Daily data were used to calculate shifts in a selection of extreme climate indices (Table 1) between 1976-2005, 2041-2070, and 2070-2100. Twenty-four hour extreme precipitation events were also examined, including consideration of 2, 5, 20, 25, 50, and 100-year events using thirty year periods. This is a relatively short period for the assessment of extremes and can lead to considerable uncertainty when estimating very rare events (e.g. 100-year return periods). However, it is not uncommon for official ECCC estimates of 100-year events to be based on shorter periods, with comparable statistical uncertainty. Subdaily extreme precipitation estimates were extrapolated from daily precipitation data for all projection sources: this includes 5, 10, 15, and 30 minute durations, along with 1, 2, 6, and 12 hours; again, 2, 5, 20, 25, 50, and 100-year return events were estimated. The same station data used in recent updates to provincial IDF curves was employed for this purpose (Conestoga-Rovers and Associates 2015).

Analysis of specific climate stations closely followed standards and procedures set forth by the Pacific Climate Impacts Consortium. NA-CORDEX and PCIC projections were downscaled to station locations using quantile delta mapping (QDM; Cannon et al. 2015). This is an extension of quantile mapping (QM), which is often used for bias correction in weather prediction and has been proposed as a means of correcting long-term climate projections (e.g., Gudmondsson et al. 2012). QDM-corrected daily data was also used to predict future precipitation IDF data, following the same procedure used by Environment and Climate Change Canada, as well as the recent IDF completed for Newfoundland and Labrador (Conestoga-Rovers and Associates 2015). Gumbel distributions were fit to annual maxima, then precipitation quantiles associated with return periods of interest were extracted. Following this approach with QDM-corrected daily precipitation gives QDM-corrected 24 hour duration intensities for desired return periods. A second QDM was performed prior to constructing the IDF curves, this time between annual daily maxima i) used for updated provincial IDF curves (Conestoga-Rovers and Associates 2015) and ii) calculated by the daily QDM-corrected PCIC/NA-CORDEX data. This removed any disagreement between the station data used in the current study and those used for the 2015 IDF update, easing comparison and ensuring consistency across IDF-related products developed for the GNL.

3.2 FLOOD RISK MAPPING

The Province of Newfoundland and Labrador, in conjunction with the federal government, has worked to reduce the human hardship and economic loss of floods through the Canada-Newfoundland Flood Damage Reduction Program (CNFDRP). Work under this program was carried out from 1981 to 1993. From 1993 to 1996 further flood studies were carried out under the federal-provincial "General Agreement Respecting Water Resource Management". This was a comprehensive agreement that included in addition to CNFDRP, groundwater management, watershed and water quality management, flow forecasting systems, water conservation economics, estuary and aquaculture management studies. Work under the CNFDRP consisted of undertaking hydrotechnical studies, identifying and mapping flood risk zones and then implementing policies to limit future flood susceptible development in those areas.

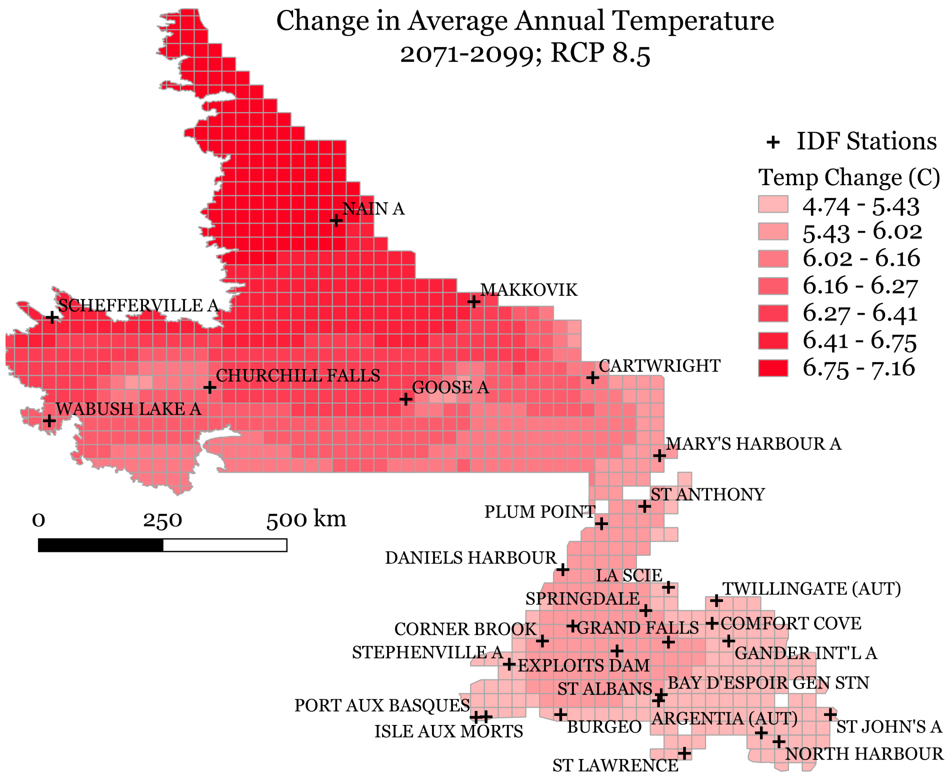

Figure 1: Domain of spatial extent of available projected climate indices for Newfoundland and Labrador. Station locations indicate where updated IDF curves are available.

After the end of CNFDRP, the first major flood risk mapping (FRM) undertaken by the province was the "Hydrotechnical Study of Stephenville" that was started in 2008 and completed in 2009. The Town of Stephenville (population 6,500), suffered record flooding in 2005 and the need for a new FRM study was identified in 2008. While undertaking the 2009 study the Water Resource Management Division realized the outdated nature of CNFDRP maps was a challenge for climate adaptation in the province. Comparing the 2007 rainfall Intensity Duration Frequency (IDF) curve with the 1990 IDF curve for Stephenville, it was evident that the 100-year 24 hour rainfall had increased 13%. Environment and Climate Change Canada's Atlantic Climate Change Office had released downscaled modelling results for Stephenville in 2008. The worst-case scenario showed 35% increase in 100-year 24 hour rainfall by 2050 resulting in a 55% increase in flows in Stephenville. The trend was changing quickly. The Stephenville FRM study used a climate change IDF in addition to the existing 20 year and 100-year 24 hour IDFs to map 1:20 AEP (annual exceedance probability), 1:100 AEP and 1:100 climate change AEP flood zones. The "Hydrotechnical Study of Stephenville" was the first provincial flood risk map in the country to include a 100-year climate change flood zone.

As a result of the 2009 study for Stephenville the Water Resource Management Division created a new template for integrating climate change into flood risk mapping. In addition to a traditional depiction of 20 and 100-year flood lines, this new template or series of steps made it possible to show the effect of climate change on flood zones. It integrates several layers of spatial data (climate change data like rainfall amounts, depth of flooding, land cover, coastal terrain) within open-source models such as HEC-HMS and HEC-RAS.

The new template for integrating climate change into flood risk mapping also included a number of features to make flood risk mapping more accurate and reproducible. These included the following.

- Since 2009, all FRM studies require that the engineering consultant undertake both a stochastic and deterministic (hydrologic modelling) approach in the estimation of the 1:20 and the 1:100 AEP. For stochastic analysis at least two applicable statistical methods, including a flood frequency analysis and a regional flood frequency analysis, are to be undertaken by the consultant.

- Since 2009, all FRM studies require that land cover analysis is undertaken using a recent high-resolution satellite imagery.

- Since 2009, all FRM studies require that a GIS based workflow is used for setting up and running the hydrologic and hydraulic models. It requires the use of HEC-GeoHMS and HEC-GeoRAS. This is to ensure that the sub watersheds are delineated in a consistent manner and that there are limited errors in data input and output.

In 2010 NRCAN funded 3 FRM studies to further develop climate change flood risk mapping template and implement climate change flood zone policy. The Province included a climate change flood zone in its "Policy for Flood Plain Management" becoming the first Province to integrate climate change into flood plain policy. The Provincial Policy for Flood Plain Management is available at http://www.mae.gov.nl.ca/waterres/regulations/policies/flood_plain.html. No Institutional development is permitted in 1:100 AEP and 1:100 climate change AEP flood zones. Other development is permitted with conditions including condition to flood proof to 1:100 climate change AEP flood elevation plus 0.6 m. Following this,

- Since 2010 all FRM studies also include a detailed hydraulic capacity assessment (based on modelling results and field surveys) of all existing hydraulic structures for the current and climate change flood flows. This helps municipalities identify which structures have inadequate capacity for current climate conditions and helps prioritize infrastructure upgrades. While the Province does not require that new infrastructure replacing existing infrastructure be designed for climate change flows, WRMD has observed that when infrastructure is being replaced in areas with climate change FRM it is being designed to handle climate change projected flows.

- Since 2012, all FRM studies require that a DEM for the entire floodplain be developed using LIDAR. This is ensures that the flood contours are accurate and allows for inundation mapping.

- Since 2012, all FRM studies require mapping of the 1:20 year AEP climate change zone.

- Since 2013, all FRM studies have to address sea level rise due to climate change. Consequently, the climate change condition has to include both precipitation increase and sea level rise. The sea-level for future climate condition is to be defined by the projections in "Past and Future Sea-Level Change in Newfoundland and Labrador: Guidelines for Policy and Planning", Geological Survey, Report 10-1, pages 129-141 available at http://www.nr.gov.nl.ca/mines&en/geosurvey/publications/CR2010/2010_Batterson-Liverman.pdf

- Since 2013, all FRM studies include flood hazard mapping associated with the 1:20 and 1:100 AEP for current climate and current development conditions based on velocity and depth of flooding. The flood hazard mapping is based on Mercedes Uden (Royal Haskoning) and Hamish Hall, (Royal Haskoning), Application of Remote Sensing (Digital Terrain Models) in Flood Risk Assessments, presentation at the National Hydrology Seminar 2007: GIS in Hydrology.

- Since 2013, all FRM studies require that the "Map-To Map" geo-processing tool, to automate the generation of climate change flood risk maps. This tool was developed in March 2012, by Dr. Dean Djokic of ESRI USA. The ArcHydro Map-To-Map Implementation Workflow is a climate change geo-processing tool that is used to automate the generation of climate change flood risk maps. The basic concept is to take a "map of rainfall" and transform it to the "map of flooding", thus Map To Map. This tool is now available to all users of ESRI ArcHydro tools. A report on the tool is available at http://www.mae.gov.nl.ca/waterres/flooding/NL_WRMD_M2M_Implementation _Workflow.pdf

- Since 2015 all FRM studies use standardized climate change scenarios and corresponding climate change IDF's from the Province's most current climate change atlas. The Province produced a climate change atlas in 2013 with climate change IDF's. These climate change IDF's were updated in 2015 and the climate change atlas is again being updated. The use of standardized climate change scenarios ensures that all climate change scenarios used are relevant to the Province's climate change adaptation action plan. Every department uses the same set of predictions.

- Since 2015 all FRM studies also account for future land use in determining the climate change flood zone. The future land is captured form the municipalities town plan and is screened in consultation with the municipal council to ensure only likely future development scenarios are included.

- Since 2015 all FRM studies must use the 2D function of HEC-RAS 2D unless the consultant can demonstrate a valid technical reason for not using it.

Since 2014, all FRM studies are used by the Hurricane Season Flood Alert System (http://www.mae.gov.nl.ca/waterres/flooding/hurricane.html) to derive precipitation based flood triggers. For every community with a FRM study the Hurricane Season Flood Alert System tracks all weather systems 72 hrs ahead and generates flood alerts from June to December. This system generated over 9630 precipitation forecasts for 45 communities/areas and issued 94 flood alerts in 2016.

All FRM studies, maps and GIS files are available on Province's Webpage at http://www.mae.gov.nl.ca/waterres/flooding/frm.html and on the NL Water Resources Portal at http://maps.gov.nl.ca/water/ Since 2009 the following FRM studies have been completed for Stephenville (2009), Stephenville Crossing/Black Duck Siding (2012), Town of Logy Bay – Middle Cove – Outer Cove (2012), Shearstown/Bay Roberts Area (2012), Goulds and Petty Harbour Area (2013), Corner Brook Stream and Petrie's Brook (2013), Portugal Cove-St. Philip's (2015), and the Waterford River (2018)

Additionally, the Province's climate change flood risk mapping template has been adopted by various consultants like CBCL Limited and KGS Group undertaking FRM studies for municipalities in Newfoundland and Labrador. The Province's climate change flood risk mapping template has been presented at several provincial, national and international workshops, conferences and meetings to much commendation. Copies of the template have been requested by consultancies and agencies across Canada and abroad.

4 COASTAL EROSION MONITORING

The GNL maintains a coastal erosion monitoring database that contains data for a range of measures used to determine rates of erosion, including nearshore geometry, sediment composition, sediment budget, and vegetation (Irivine 2014). There are a total of 112 sites in the province, 103 of which are on Newfoundland, with 9 in Labrador. These sites are monitored on an annual, biennial, or triennial cycle, depending on the locaton. The primary goals of this program is to provide estimates of changes along the coast over time, identify areas that are vulnerable to coastal erosion, and understand how the coast may change in the future (Irvine 2014).

Sea level rise due to climate change is expected to have a significant impact on coastal evolution. Isostatic changes in land surface will exacerbate coastal erosion in combination with sea lever rise in some areas, such as on the Avalon Peninsula (Batterson and Liverman 2010). Overall, these impacts will most likely lead to greater exposure of the base of cliffs to larger waves due to storm surge and increased fetch, and higher sea levels for a greater period of time (less sea ice). Additionally, increase erosion from surface water, ground water (which can promote creep, slides, and slumps on coastal bluffs), and wind is expected as well (Irvine 2014).

Over 90% of the population of NL lives near the coast, and a significant portion of the province's infrastructure in coastal areas may potentially be affected. Coastal infrastructure has already been impacted in many parts of NL, such as Placentia, and the monitoring program has identified several communities that may be particularly vulnerable. The information provided by the GNL on coastal monitoring is of direct relevance to the planning and design of infrastructure that may be impacted by coastal erosion and changes in sea level to do climate change.

5 OUTREACH AND FURTHER RESEARCH

The tools described above represent a good start towards incorporation of non-stationarity and climate change into important aspects of planning and design of infrastructure. As part of the NRCan BRACE (Building Regional Adaptation Capacity and Expertise) program, MUN and GNL hosted a workshop in March of 2018 that provided an overview of the climate change projections for the province, the tools available that allow for incorporation of climate change into planning and design, and the coastal monitoring program, all as described above. A second workshop is to be held in April 2019 that continues training of professional engineers and planners in climate change considerations in asset management and the emerging legal framework in NL and Canada regarding climate change and professional liability.

There is ongoing work from both the GNL and Memorial University towards the continued development of knowledge and tools addressing climate change. For instance, the Province is now working with an engineering firm to develop an automated system to feed weather forecasts into Hydrologic and Hydraulic models used in FRM studies to have real time flood forecasting. There has been continued work in the area of the development and application of design storms in NL (Amponsah et al. 2019), and this work is being extended to include the updated IDFs along with other potential impact of climate change on storm water infrastructure.

Additionally, the NRCan funded project includes the establishment of a special working group that will work to identify and prioritize current knowledge gaps in the understanding and integration of climate change into infrastructure planning and development, including climatological, hydrological, and ecological effects. The group would be engaged in providing input and expertise, to inform the development of (1) a comprehensive survey of current climate change knowledge and gaps in NL; and (2) sample design projects (real and hypothetical) examining aspects and differences between a traditional approach and one that includes adaptive capacity.

In summary, considerable challenges remain regarding how to use existing and new knowledge to build resilience and adaptive capacity into storm water infrastructure and all civil infrastructure. This gap in our knowledge includes both “know-what” and “know-how” in applying concepts and results of risk and resilience assessments for climate change adaptation to real world systems. Most simply, resilience entails functioning and delivery of services during or quickly after a disturbance. Engineering resilience in design has been focused on robustness, so that a robust structure, for instance, can withstand a disturbance or series of disturbances and remain, and has been a core part of infrastructure for long time. Traditional approaches to engineering design are often focused on optimization of reliability and engineering resilience. However, infrastructure resilience to climate change does not apply to a single piece of infrastructure; resilience is a property of a system (Walker and Salt 2006). Key characteristics of resilience include diversity, redundancy, modularity, ecological variability, social capital, agency, inclusiveness, tight feedbacks, innovation, and ecosystem services that are set within socio-economic-ecological systems (Gibbs et al. 2017). The currently available tools described above, and the work currently being done by MUN and GNL represent a small piece of the much larger goal of building resilient infrastructure and incorporating climate change into infrastructure planning and design.

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