Appendix A

Climate Change Assessment

(Risk Sciences International, 2019)

Ridge Landfill Future Design Storm Values - Brief Description of Extreme Rainfall Projection Methodology

Methodology and Theoretical Basis

A reality is that climate change models – whether global climate models (GCMs) or regional climate models (RCMs) - have limited ability to simulate and project extreme rainfall since typical model spatial resolutions are too coarse to resolve important small-scale processes such as convection (i.e., thunderstorm activity). Climate change models (GCMs and RCMs) have been found to perform poorly in simulating past rainfall extremes, typically underestimating extreme amounts and showing large differences between different models and approaches. For example, in comparing extreme rainfall projections, Coulibaly et al. (2016) and Switzman et al (2017) assessed the outcomes of several different future climate IDF statistical downscaling approaches for selected southern Ontario regions and found a range of results. The results indicated significant variability among the various future IDF projections, resulting in a large range of rainfall intensity values for different storm durations and return periods, and a lack of robustness to support or identify a "best" approach. The variability was greatest for the more extreme storms. The large uncertainties and differences between climate models and approaches for downscaling of sub-daily precipitation extremes were highly influenced by the choice of climate model, downscaling method, greenhouse gas emission scenario and statistical methodology used for producing the projections of extreme IDF.

While there is an expanding body of research on the development of future climate change driven IDF values, many of these approaches are still experimental with results that are often inconsistent and have large uncertainties (Coulibaly et al., 2016; Mirhosseini et al., 2013). However, when climate change "adjustment factors" or augmentation factors are needed, climate research increasingly supports some defensible but simple future climate approaches for extremes. These approaches are founded on the Clausius-Clapeyron relation, which is a theoretical relationship between air temperature and the amount of water the air could potentially hold. The theory indicates that an increase in air temperature of 1°C corresponds to a rough increase of ~7% for heavy rainfall in Canada and the United States, provided that potential sources of moisture are not limited. In addition, the few studies that have managed to downscale global climate projections using regional and finer scale models with resolutions fine enough to actually attempt to simulate convection down to 1 to 4 km indicate that the longer duration rainfall extremes increase at around the Clausius-Clapeyron scaling rate (7% per 1°C warming), while shorter-duration convective extreme rainfall may increase at a super Clausius-Clapeyron rates from 7% to as much as 14%.

251 LAURIER AVENUE W., SUITE 700 | OTTAWA, ON K1P 5J6 | CANADA | TEL: 613.260.1424 | FAX: 613.260.1443
www.risksciences.com

Numerous observational studies – studies comparing changes in rainfall rates from observed storms with concurrent temperature measurements – have shown that this temperature scaling relation is very well correlated with changes in rainfall intensity across different regions. Barbero et al. (2017), for example, found increases of ~6.9% per 1°C increase for the United States during the 1950-2011 period. In Canada, Panthou et al. (2014) analysed extreme rainfall intensity against air temperature for 5-min to 12-hr duration storm events and found current extreme rainfall relationships that were close to 7% per 1°C increase for coastal regions. s Lower increases or temperature scaling relationships were observed with longer rainfall durations in inland regions (i.e., smaller ratios than the 7% per 1°C at the 12-hr duration). Prein et al. (2016) found that extreme precipitation intensities increased in nearly all regions of the Contiguous U.S. and southern Canada during the 2001-2013 period, with a domain median intensification of 6.7% per 1°C warming.

Extreme precipitation events represent the most efficient translation of moisture in the air into rainfall, meaning that "the heaviest precipitation events are likely to occur when effectively all the moisture in a volume of air is precipitated out" (Westra et al., 2014). Hence, the Clausius-Clapeyron relation provides a method rooted in a strong physical basis to help determine the potential future effects of climate warming on extreme rainfall. With scientific confidence being highest for climate change projections of atmospheric temperatures, there is reasonable confidence that the Clausius-Clapeyron relation can be used as a first guess to project ranges of potential increases in daily extreme rainfall for mid to high latitude regions (Westra et al., 2014).

Temperature projections for the study area are/were based on an ensemble of the latest global climate models (GCMs) associated with the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report (AR5). Projections are based on the Representative Concentration Pathway (RCP) 8.5 scenario, also knows as the "business as usual" emissions pathway, intended as a "conservative" or "risk averse" estimate of future warming corresponding to little or no greenhouse gas (GHG) emissions reductions. The Australian Rainfall & Runoff Guide (Ball et al., 2016) recommends the use of this Clausius-Clapeyron based method for first projections of rainfall extremes and future IDF values in Australia. Similarly, the new edition of the CSA PLUS 4013 IDF Guidelines for Canadian water resource practitioners (CSA, 2019; in review) recommends this approach. Other more sophisticated and finer scale approaches can be applied where high levels of resources and expertise are readily available.

Analytical Results

IDF curves for Ridgetown (Ridgetown RCS; ID: 6137154) and Chatham-Kent (Chatham WCPC; ID: 6131415) were adjusted using the Clausius-Clapeyron relation based methodology. A lower end 5%-per-degree increase in rainfall intensity was used, based on Panthou et al.'s (2014) observational rainfall intensity-temperature relationship for the study area (i.e., Great Lakes basin). This rate of change is also suited to the long-duration 24-hour rainstorm events being adjusted, which tend to correlate with a lower rate of rainfall intensity change (i.e., temperature-rainfall intensity change is below 7% per degree).

Projected future temperatures for the 2050s and 2080s for each of the IDF station locations are obtained from the ensemble of GCMs. Temperature is based on the projected change in mean maximum daily temperature, as specified in Wang et al. (2017), which is considered the most representative air temperature corresponding to heavy rainfall events. The Clausius-Clapeyron Scaling factor for the study area, using the following equation, with a 5% scaling for 24-hour storms, as indicated above:

$$(1) \quad CC_{adj} = (CC_{factor} * \Delta T_{loc}) + 1$$

where $CC_{factor} = 0.05$ for 24-hour storms, and ΔT_{loc} is the projected location specific projected change in mean maximum daily temperature.

The new storm rainfall amount is then determined by a scaling of the current storm amounts in a multiplier, using the CC_{adj} scaling factor from Equation 1:

$$(2) \quad R_{adj} = CC_{adj} * R_{curr}$$

where R_{curr} is the current rainfall amount and CC_{adj} is the product of the CC scaling equation above.

The results of the projections are provided below in

Table 1 (Ridgetown) and Table 2 (Chatham-Kent). The 25th and 75th percentile values are based on the 25th and 75th percentile temperature change outputs from the climate model ensemble and provide a description of projection uncertainty.

Table 1 - Adjusted future 100-Year and 250-Year 24-hour rainfall amouts for Ridgetown IDF station. All rainfall amounts reported in mm.

Adjusted 100 year, 24-hour storm			
Ridgetown			
	25th Percentile	Mean	75th Percentile
Current		121.9	
2050s	137.7	140.8	145.1
2080s	148.1	153.6	159.1
Adjusted 250 year, 24-hour storm			
Ridgetown			
	25th Percentile	Mean	75th Percentile
Current		136.5	

2050s	154.2	157.6	162.4
2080s	165.8	171.9	178.1

Table 2 - Adjusted future 100-year and 250-year 24-hour rainfall amounts for Chatham-Kent IDF station. All rainfall amounts reported in mm.

Adjusted 100 year, 24-hour storm			
Chatham-Kent			
	25th Percentile	Mean	75th Percentile
Current		100.3	
2050s	113.3	115.8	119.4
2080s	121.9	126.4	130.9
Adjusted 250 year, 24-hour storm			
Chatham-Kent			
	25th Percentile	Mean	75th Percentile
Current		110.8	
2050s	125.2	128.0	131.9
2080s	134.7	139.6	144.6

Caveats

Statistical Assumptions

The new return period rainfall values assume that the current temperature to extreme rainfall scaling relationship holds and that the distribution and contribution of the different types of extreme rainfall events to the IDF curves remains unchanged into the future. This means that, as informed by historical mean and standard deviation of rainfall events at each IDF station, the statistical characteristics of rainfall behaviour are unchanged; i.e. only the means of the extreme values changes. The current IDF rainfall distribution is fully based on historical observations, which may not remain static under new climate conditions.

Differences in baseline values: Ridgetown versus Chatham-Kent

IDF curves are particularly sensitive to peak extreme rainfall values within their observational dataset, and significant differences in long-return-period storms can occur if a station samples an unusually intense extreme rainfall event. The Ridgetown station sampled two large rainfall events – two 24-hour storms with over 95 mm in 1962 and 1985 – which represent more extreme data points within a shorter period of record than the highest values recorded at the Chatham-Kent station's longer period of record (30 years of data versus 40 years, respectively). This has led to a "steeper" IDF curve that increases more rapidly with longer return periods at the Ridgetown station when compared to the Chatham-Kent station. In general, IDF point data may be highly influenced by either the absence or inclusion of a

251 LAURIER AVENUE W., SUITE 700 | OTTAWA, ON K1P 5J6 | CANADA | TEL: 613.260.1424 | FAX: 613.260.1443
www.risksciences.com

particular outlier event, especially in areas where thunderstorms tend to influence the critical design criteria and when available precipitation series are short.

References

Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors). 2016. Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia (Geoscience Australia).

Barbero, R., H.J. Fowler, G. Lenderink and S. Blenkinsop. 2017. Is the intensification of precipitation extremes with global warming better detected at hourly than daily resolutions? Geophysical Research Letters, 44 (2): 974-983.

Canadian Standards Association (CSA) 2019. TECHNICAL GUIDE – Development, interpretation, and use of rainfall intensity-duration-frequency (IDF) information: Guideline for Canadian water resources practitioners. 3rd Edition, unpublished manuscript, in-review. 209 pp.

Coulibaly, P., D.H. Burn, H. Switzman, J. Henderson and J. Fausto. 2016. A Comparison of Future IDF Curves for Southern Ontario. Ontario Climate Consortium, Toronto, ON. Available online: https://climateconnections.ca/app/uploads/2014/01/IDF-Comparison-Report-and-Addendum.pdf

Mirhosseini, G., P. Srivastava and L. Stefanova. 2013. The impact of climate change on rainfall Intensity-Duration-Frequency (IDF) curves in Alabama. Regional Environmental Change, 13 (Suppl. 1): 25-33.

Panthou, G., A. Mailhot, E. Laurence, and G. Talbot. 2014. Relationship between Surface Temperature and Extreme Rainfalls: A Multi-Time-Scale and Event-Based Analysis. Journal of Hydrometeorology, 15 (5): 1999-2011.

Prein, A.F., R.M. Rasmussen, K. Ikeda, C. Liu, M.P. Clark and G.J. Holland. 2016. The future intensification of hourly precipitation extremes. Nature Climate Change, 7: 48-52.Switzman, H., T. Razavi, S. Traore, P. Coulibaly, D.H. Burn, J. Henderson, E. Fausto and R. Ness. 2017. Variability of Future Extreme Rainfall Statistics: Comparison of Multiple IDF Projections. Journal of Hydrological Engineering, 22 (10): 1-20.

Wang, G., D. Wang, K.E. Trenberth, A. Erfanian, M. Yu, M.G. Bosilovich and D.T. Parr. 2017. The peak structure and future changes of the relationships between extreme precipitation and temperature. Nature Climate Change, 7: 268-274.

Westra, S., H.J. Fowler, J.P. Evans, L.V. Alexander, P. Berg, F. Johnson, E.J. Kendon, G. Lenderink and N.M. Roberts. 2014. Future changes to the intensity and frequency of short-duration extreme rainfall. Reviews of Geophysics, 52 (3): 522-555.

251 LAURIER AVENUE W., SUITE 700 | OTTAWA, ON K1P 5J6 | CANADA | TEL: 613.260.1424 | FAX: 613.260.1443
www.risksciences.com