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ABSTRACT: This paper describes a small study carried out using a hygrothermal simulation tool to investigate the sensitivity of wall performance results to uncertainty in the amount of rain impinging on the wall. Design standards for hygrothermal analysis of proposed designs include methods for selecting appropriate moisture reference years and specify the amount of water that is assumed to intrude into the wall. Weather data used as input for modeling purposes is generally assumed to be reliable, but recent work has shown that there may be considerable uncertainty in the rainfall data. A small study was carried out to investigate the effect of uncertainty of rainfall data on the hygrothermal performance of a typical residential building envelope. Most hygrothermal models require fully populated hourly datasets, which include rain data. Many locations, however, do not have this kind of data although many have qualitative rain data. Ten locations with rain gauge data were chosen as typical of most regions of Canada, except for the far north. Different methods in estimating rainfall were considered as well as variations on the amount of rain data were subsequently made. Several performance criteria, including total moisture content and a mould index, were compared. Although the choice of which method for deriving quantities of water from qualitative codes does cause differences in the hygrothermal response and consequently the performance criteria, these differences appear to be manageable. It is suggested that practitioners should show their awareness of the probable level of uncertainty by stating error bands for their predictions of performance. It should be emphasized that the sources of uncertainty dealt with in this small study are not the only ones, but that they do focus on water entry through leakage paths. The natures of the leakage paths likely introduce greater uncertainty, and should also be borne in mind.

KEYWORDS: hygrothermal simulation, moisture, design, weather data, rainfall, uncertainty, building envelope

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INTRODUCTION

Building science practitioners in assessing the performance of building envelopes and whole buildings are increasingly using hygrothermal simulation tools. The equations for heat, air, and moisture transfer are well understood and there exist many hygrothermal simulation tools, some commercially or publicly available, and others laboratory or research tools [1][2][3][4]. Confidence in the accuracy of these tools is readily achieved through the use of verification and validation [5]. Many of these tools are being used to generate the input data for damage models, which are used to assess the response of building envelope components, and predict the service life [6][7]. Moisture design standards for hygrothermal analysis, such as ASHRAE 160-2009 [8], give guidance and help to practitioners through what can be a complex process. Part of the process is selecting the appropriate weather data for simulation studies. Much work has been done on selecting appropriate moisture reference years for hygrothermal simulation work [9][10][11][12][13]. However, despite the accuracy and robustness of the simulation tools the common rubric suggests that the end results are only as good as the input data. Sources of uncertainty in input data include but are not limited to materials property data, boundary conditions, interior conditions, and weather data. Holm and Kunzel [14] examined the sensitivity of hygrothermal analyses to uncertainty in measurements of material properties data by varying the properties stochastically within the range of measurement data. Perhaps the next most important parameter to examine is the weather data. Weather data used as input for hygrothermal modeling purposes is generally assumed to be reliable, but recent work has shown that there may be considerable uncertainty in the rainfall data [15]. Several comprehensive studies by Blocken and Carmeliet [16][17][18][19] have examined uncertainties in wind-driven rain calculations. They suggest a combined CFD-HAM approach for assessing the moisture performance of buildings [20]. In their 2000 study [19] they demonstrated that even hourly sampling is not good enough and that averaging errors generated in producing hourly wind and rain data can produce large errors in wind-driven amounts. They suggest that ten-minute data are required. In reality, however, ten-minute coincident rain and wind data are rare. In fact, obtaining any kind of rainfall data at all can be problematic. Most hygrothermal models require fully populated hourly datasets. Many available rain data, however, are not hourly. Commonly 6- or 24-hour totals are available. In some cases hourly observations are available but these observations tend to be qualitative rather than quantitative. There is a wealth of scientific literature on estimating rainfall from sparse data; however, most of the work is related to hydrology or agriculture [21][22]. Koronthályová and Matiašovský [23] published a method for generating hourly wind-driven rain amount values from daily courses of driving-rain and Cornick and Dalgliesh [15] examined various methods for converting qualitative rain observations to quantitative values. In that work various methods for fully populating datasets of qualitative data, such as “light rain,” with quantitative hourly rainfall intensities were examined. How sensitive are hygrothermal simulations to these uncertainties in rain data or the methods used for producing simulated rain data?

A comprehensive hygrothermal study, MEWS, was undertaken in which the amount of water penetration in the wall was a parameter [24]. The goal of the study, however, was not explicitly to examine the sensitivity of the envelope response to variations in rain. The study modeled many different wall configurations and the results showed that the response was sensitive to variations in rainfall for some cases and insensitive for others. A study carried out by Tariku et al. [2] demonstrated that building envelopes could be sensitive to the amount of rain impinging on the surface and penetrating the exterior. This study examined the effect of varying the amount of water penetrating a stucco-clad wall. The amount of water entry was proportional to the amount of water striking the wall. Water penetration was varied from 0.5–4 % of the wind-driven rain striking the wall. In the study the amount was varied either up or down until the failure criterion was reached in the case of increasing the rainfall or the failure criterion was not met in the decreasing case. The study showed (among other things) that for rainy locations failure of this particular wall occurred at a water penetration ratio of 0.5 %. A similar wall was used for the present study.

In 2000 Matiašovský and Koronthályová [25] published a study examining the sensitivity of the hygrothermal performance of an external wall to uncertainty in driving-rain data. In this study hourly estimates of wind-driven rain were estimated from six-hourly values. The hygrothermal response of thick (~ 300 mm) masonry walls was compared. The reference performance was obtained by using an hourly dataset measured by the Fraunhofer Institute für Bauphysik, Holzkirchen in 1991. The weather set for comparison was generated from six-hourly wind-driven rain totals. The comparison showed that for the masonry walls there was little sensitivity.

Since most of the studies except for the last quoted dealt with uncertainty in rainfall indirectly, a small study was carried out to investigate the effect of uncertainty of rainfall data on the hygrothermal performance of a typical residential building envelope. Ten locations with tipping bucket rain gauge data were chosen as typical of most regions of Canada, except for the far north. Each location has at least 30 years of rainfall intensity data (except the near arctic location). In terms of variations the rain gauge data were assumed to be correct although too much faith should not be placed in this assumption [15]. Several performance measures were used to assess the responses to the different rain inputs: the total moisture content, a mould index, and a time-of-wetness indicator.

MODELING STUDY

A commercially available one-dimensional hygrothermal model was used for the simulation study [3]. This particular tool is geared towards building science practitioners. It was selected rather than the two-dimensional research version of the same program so that the results would be representative of common practice. The governing equations for the simulation tool are given by Tariku et al. [2]. The modeling study consisted of simulating a wall selected to be responsive to moisture loads and applying the loads to the exterior as well as allowing for some water penetration for various locations. The response of a moisture sensitive portion of the wall was then examined. It should be noted that the purpose of the exercise was not to determine whether the given wall performed adequately, or passed or failed, but rather to investigate the response to changes in the moisture load. Details of the study are given below.

Wall Configuration

The wall configuration used in the study is given in FIGURE 1. This wall configuration has been used in several studies previously [24][2]. The wall comprises, from exterior to interior, 20 mm Portland Cement stucco, 0.2 mm of asphalt saturated paper (ten-minute paper), 11 mm of Oriented Strand Board (OSB), 140 mm of low density glass-fibre insulation, a sheet of 6-mil polyethylene (0.2 mm), and finally 12.7 mm of gypsum board with primer and latex paint. The materials selected came from the stock library of the hygrothermal tool used.

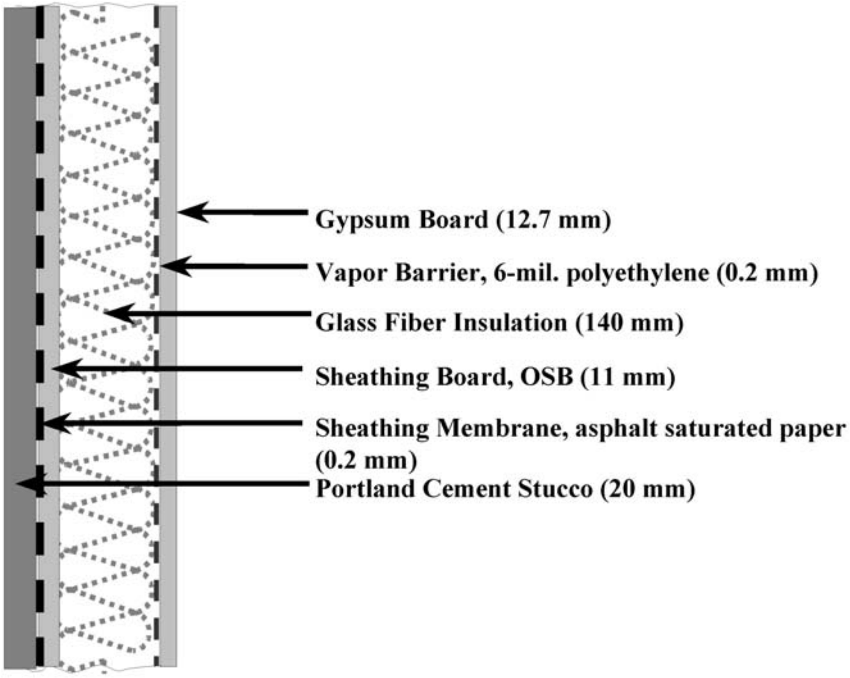

FIGURE 1—Schematic diagram of stucco wall cross-section under study.

Geographic Locations

Ten locations representative of Canadian climate types were selected for the rain sensitivity study. The climates vary from cool marine climates to semi-arid to arctic climates. The locations and some basic climate parameters are given in TABLE 1.

TABLE 1—Locations selected for the simulation study. The table includes the mean annual rainfall (30-year average), standard deviation of the rainfall, tenth percentile cold year as per ASHRAE 160-2009 [8], and the mean temperature for the cold year.

Location	Mean annual rainfall [mm]*	Standard deviation [mm]	Mean annual temperature [ºC]	10th percentile cold year	Mean cold year temperature [ºC]
Vancouver Int'l A, BC	1155	130	10.1	1972	9.1
Calgary Int'l A, AB	321	80	4.1	1969	2.6
Regina A, SK	304	73	2.8	1965	1.0
Winnipeg Int'l A, MB	416	87	2.6	1972	1.1
Windsor A, ON	805	168	9.4	1972	8.5
Ottawa Int'l A, ON	732	103	6.0	1978	5.1
Montreal Int'l A QC	764	117	6.2	1972	5.1
Iqaluit A, NU	198	94	-9.8	1978	-11.2
Shearwater A, NS	1254	372	6.7	1972	5.7
St John's A, NF	1191	213	4.7	1993	3.8

* Rainfall amounts do not include solid forms of precipitation, such as snow, hail, or melt water.

Boundary and Initial Conditions

The establishment of the exterior and interior boundary conditions was based on Standard 160-2009 [8]. The model used, like most hygrothermal models, requires fully populated datasets. The dataset parameters comprise dry bulb air temperature, relative humidity, total solar and diffuse insolation on the horizontal surface, mean wind speed and direction, hourly rainfall intensity, and a cloud index. The Standard offers a choice between running a ten-year continuous simulation or single Moisture Design Reference Years (MDRYs) defined as the tenth percentile warmest and tenth percentile coldest years from a 30-year weather analysis. Work by Salonvaara et al. [11] on selecting weather for hygrothermal analysis will possibly change criteria in the Standard 160-2009 but the recommendations of this work were not available at the time of writing. The new methodology, however, will not change or remedy the situation regarding uncertainty in the climate data. For the simulation study the tenth percentile coldest year was selected for the simulation. This year was assumed to have the least amount of drying potential for the simulated walls. Although there were extensive historical data for all the locations considered, only the years where tipping bucket rainfall data were available were considered. Thirty or more years of tipping bucket data were available for all the locations except for Iqaluit, for which there was only 16-years. The tenth percentile cold years chosen for each location are given in TABLE 1. These years form the basis for the parametric variation of rainfall. The exterior heat transfer and moisture transfer coefficients were initially set to 30 $W/m^2 \cdot K$ and $2.07 \cdot 10^{-7}$ m/s, respectively.

The interior conditions were also based on Standard 160-2009. The assumption was that the interior space was heated but not air-conditioned. The recommended indoor temperature and relative humidity conditions are outlined in TABLE 2. The interior heat transfer and moisture transfer coefficients were initially set to 8 $W/m^2 \cdot K$ and $5.8 \cdot 10^{-8}$ m/s, respectively.

The initial conditions were determined by running the model for one year using the year chosen for simulation without any rain data. The temperature and moisture conditions in the wall at the end of the year were used as the initial conditions for the parametric runs. This was done for each location.

TABLE 2—Indoor design temperature and relative humidity (from [8]).

24-hour Running Average of outdoor temperature [°C]	**Indoor temperature [°C]**	**Daily average outdoor temperature [°C]**	**Design RH [%]**
$T_{o,\,24h} < 18.3$	21.1	Below -10	40
$18.3 < T_{o,\,24h} < 21.1$	$T_{o,\,24h} + 2.8$	$-10 < T_{o,\,daily} < 20$	$40 + (T_{o,\,daily} + 10)$
$T_{o,\,24h} > 21.1$	$T_{o,\,24h} + 2.8$	Above 20	70

Parametric Variations

Having established the tenth percentile cold year for the simulation runs and the initial conditions, the hourly rainfall intensities were varied. Two baseline years were selected for variation, the first consisting of tipping bucket data (also used as the reference year for comparison purposes) and the second comprising weather observation codes from the present weather observations. Rainfall intensities for the weather observation codes were determined from the values recommended by Environment Canada [26] [27]. Cornick and Dalgliesh [15] discuss in detail the conversion of weather observation codes to hourly rainfall intensities. Variations on both these base years consist of increasing and decreasing the rainfall intensities by 20 %. The 20 % amount generally bounds the error between the tipping bucket and estimated rainfall data, or both, and the climate normal data[3]. Variations of the observation codes consist of varying the recommended intensities in order to minimize the error between the estimated long-term means and measured long-term means [15]. The variations are summarized in TABLE 3. FIGURE 2 shows the difference in rainfall striking the wall for the Calgary cold year. For the location in FIGURE 2 quantitative data, in the form of tipping bucket data, were available as were qualitative data in the form of weather observation codes.

Two things are immediately apparent from the figure. The first is the difference in magnitude of rainfall amount and the second is the lack of synchronicity of the rainfall records. This phenomenon is discussed in detail by Cornick and Dalgliesh [15]. Briefly, the EC rainfall amounts were derived from weather observations made by a trained weather observer (a task increasingly now automated). The observations for rainfall and drizzle fall into the one of three categories, light, moderate, or heavy. The rainfall amounts for the hygrothermal input files were constructed by assigning the values recommended by the local meteorological service for each category, assuming that the intensity persists for the hour. The recommended values for the intensities do not necessarily reflect the typical rainfall of a specific location or account for observer bias. Estimates of rainfall based on qualitative data therefore can over- or underestimate quantitative measures for the same event for a variety reasons. The observation system was designed for aviation purposes and not for hygorthermal modeling. Cornick and Dalgliesh [15] discuss ways of improving the estimates by adjusting the recommended intensity values using long-term climate normal data. None of this is ideal; however, there are many more stations where qualitative rain data are available than there are stations where qualitative data are available.

Records of tipping bucket data were obtained from the local meteorological service, Environment Canada. The instruments were located at or near the locations where the weather observations were made. Cornick and Dalgliesh [15] also discuss some of the difficulties with tipping bucket data. Perhaps the most significant problem is related to solid precipitation. In general the tipping data were obtained from tipping buckets that were not heated, consequently any solid precipitation or mixed solid and liquid precipitation was excluded from the dataset. Generally the tipping buckets do not record precipitation during the winter period. FIGURE 2 also shows some asynchronous portions outside the winter period. Another possibility is that some rainfall events occur when the observer is not looking. As ridiculous as that sounds observers are trained to make observations on the hour. Events occurring between regular observations may be recorded in special files but are generally not reported [15]

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[3] The terms "climate averages," "climate means," or "climate normals" are synonymous. Climate normals are arithmetic calculations based on observed climate values for a given location over a specified time. The World Meteorological Organization considers 30 years long enough to eliminate year-to-year variations. For Canada, the current period of record is 1971 to 2000.

TABLE 3—Parametric variations and codes

Rainfall intensity	Code
Zero rain case; i.e., rain has been turned off	ZC
Tipping bucket data	TB
Tipping bucket data –20 %	TB-20
Tipping bucket data +20 %	TB+20
Environment Canada observation codes	EC
Environment Canada observation codes –20 %	EC-20
Environment Canada observation codes +20 %	EC+20
Environment Canada observation codes—adjusted Light amount	EC-L
Environment Canada observation codes—adjusted Light, Moderate, Heavy amounts	EC-LMH
Stochastic model—observation code amounts set using Weibull distribution	EC-S

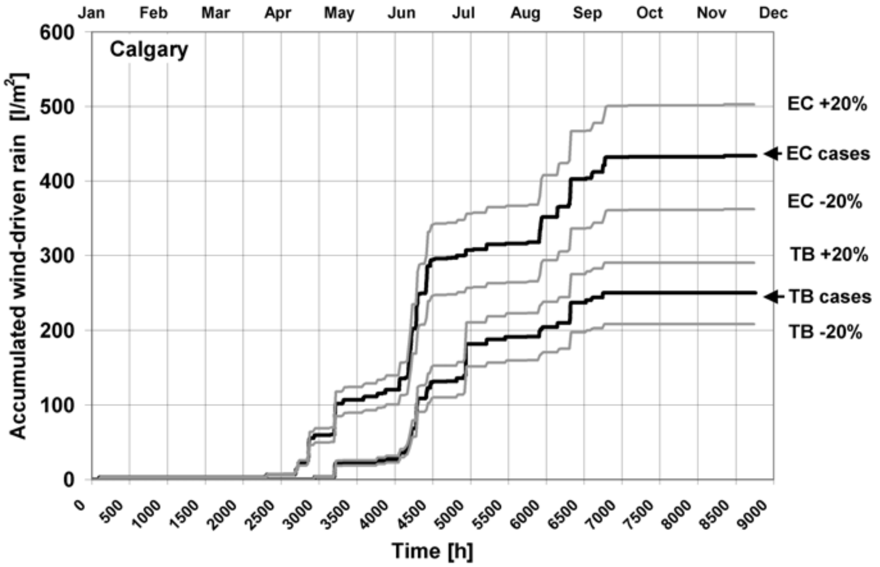

FIGURE 2—Accumulated rain striking the wall for variations in the weather file. The location is Calgary and the wall orientation is north, the direction that sees the most wind-driven rain. The grey lines represent the 20 % bands from the EC and TB cases (black lines). All variations are within the 20 % bands.

Modeling Assumptions

With respect to rain penetration the default values from Standard 160-2009 were used, specifically the water penetration through the exterior was set at 1 % of the water that reached the exterior surface (see FIGURE 2). The deposit site for the water was the exterior surface of the sheathing membrane as recommended. Since no guidance is given in the Standard, the water is assumed to be deposited along the full height and length of the wall, 1 m^2 in the case of the one-dimensional simulation. Although the Standard recommends a method for calculating the design rain load on the wall when a comprehensive wind-driven analysis is not performed, it was not used. This was because the hygrothermal tool used has built into it a similar method for calculating the amount of wind-driven rain [28]. The walls were oriented in the direction of predominant long-term wind driven rain; i.e., the corridor which accumulates the most wind-driven rain over 30 years or more. Each corridor sweeps out an angle of 45°, the first being centered on North.

Although the Standard recommends a 5 Pa positive pressure during the heating season and a 5 Pa negative pressure during the cooling season this was not applied. The one-dimensional model did not permit the modeling of air-leakage paths nor the scheduling of interior pressure regimes. In any case, the presence of the polyethylene sheet effectively prevents the movement of air through the materials, consequently it was felt appropriate to ignore this requirement.

Response

Three measures for evaluating the response of the wall were used. The first method was the calculation of a Mould Index, MI. This index was based on the work of Hukka and Viitanen [29][30][31] and its implementation described by Nofal and Kumaran [7] and Nofal and Morris [32]. The index ranges from 0–6 with a value of 4 being considered the threshold of failure. A second measure of response, the RHT index, is taken from Kumaran et al. [33]. RHT is a measure of risk of moisture related damage to wood-based products. Two thresholds determine the risk, a temperature threshold of 5ºC and a RH threshold. For this paper the RHT80 index was used; i.e., the RH threshold was set at 80 %. The index is defined by Eq. 1. If either term in the product is negative the index is zero. The sum of the index over time provides a measure of overall risk [24].

$$RHT80 = (RH - 80)(T - 5) \quad [°C\ \%] \qquad \text{Equation 1}$$

Where: RH is the relative humidity at the point of interest, [%]
T is the temperature at the point of interest, [°C]

The third response measure used was the moisture content (MC), defined as the mass of water per dry mass of material (kg/kg). With respect to selecting the point of interest to measure the response the point of interest was selected to be the first node inward from the exterior of the OSB layer that was not saturated in the worst-case scenario. A 98 % RH threshold was set as the criterion in order to ensure that there was a measurable response. In some cases the point of interest was the exterior surface of the OSB layer whereas in others it was somewhere in the middle of the OSB layer. For the purposes of this work the tipping bucket data, or TB case, were used as the reference case for comparison. The different variations were compared using the following methods. For each location the MI, RHT80 index, and MC for the point of focus was calculated. For the MI and moisture content the Mean Bias Error was calculated. For the RHT80 index the cumulative total at the end of the simulation time was used. Throughout this work ASHRAE Standard. 160-2009 [8] was used as an input guide. However, the evaluation criteria specified in the standard were not appropriate for this exercise. The criteria were intended to be used as pass-fail criteria. The standard sets out maximum thresholds for surface RH to prevent problems associated with mould growth. Although criteria set out in ASHRAE 160-2009 could be considered a time-of-wetness measure it was found that the measure, was insensitive to the parametric changes used in this study and consequently of limited use, especially the 98 % and 100 % threshold limits. In order to compare the different locations the change in input was normalized to the TB case. In other words the amount of rainfall striking the wall was calculated as the ratio of the amount of rainfall striking the wall for a parametric case and the amount of rain striking the wall for the TB case.

A cautionary note is in order here. It was not the intent of the work to examine the performance of the wall or estimate the risk of moisture damage or make any judgment as to the appropriateness of the construction. The study was designed to probe sensitivities of the structure so as to gauge the effect of changes in the precipitation input.

RESULTS

Typical of modeling studies, results of interest must be rescued from obscurity among the mass of data generated by the simulations. Such results are exemplified in FIGURE 3, FIGURE 4, and FIGURE 5. The figures show the response to variations in rainfall of the first node in the OSB where the RH is less than 98 % in the worst-case scenario. In the Calgary case this occurs about 0.1 mm in depth from the exterior of the OSB. FIGURE 3 shows the time series variation of MI while FIGURE 4 shows the same but for MC. FIGURE 5 shows the progressive accumulation of RHT80 at the point of focus.

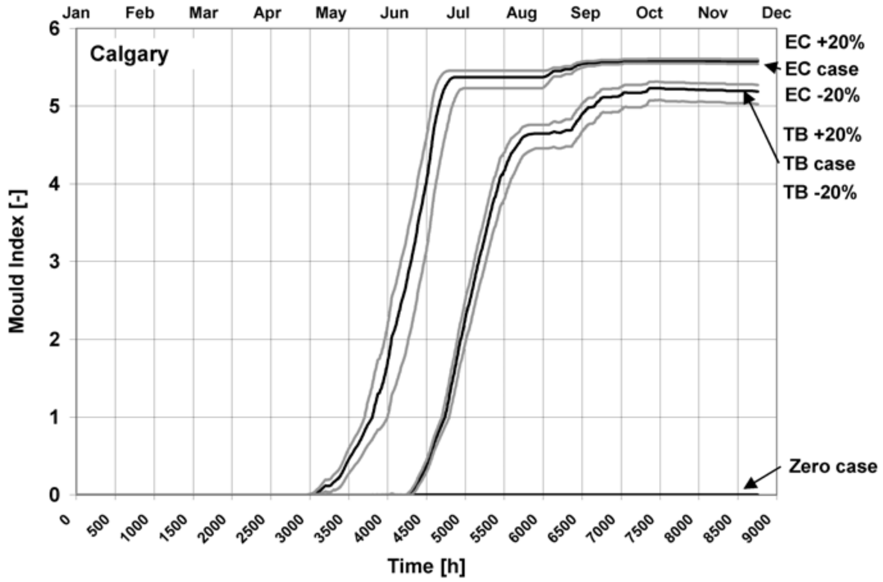

FIGURE 3—Time series of the mould index for the parametric variations for Calgary AB. For each set of cases (EC and TB black lines) all the parametric variations are within the 20 % boundaries (grey bands). Note that the mould index was zero for the ZC variation.

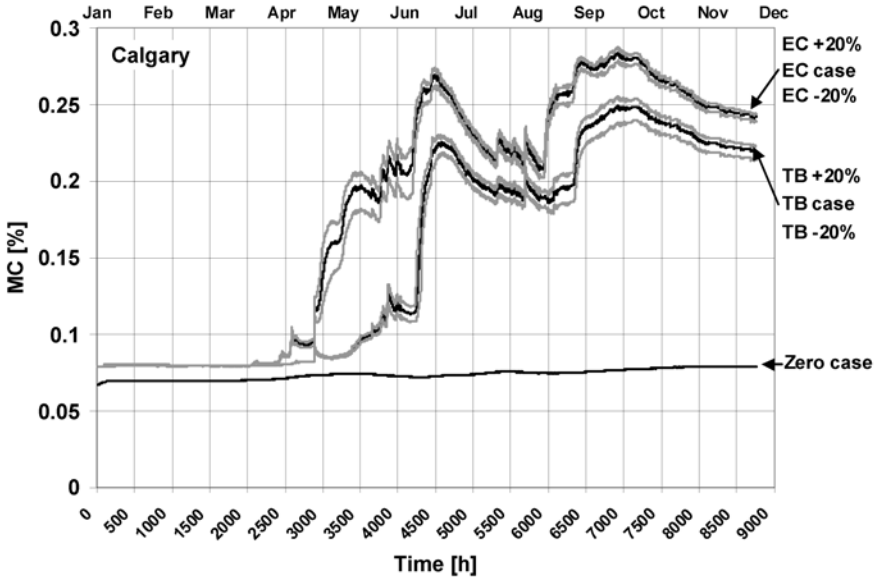

FIGURE 4—Time series of the moisture content for the parametric variations for Calgary AB. For each set of cases (EC and TB black lines) all the parametric variations are within the 20 % boundaries (grey bands).

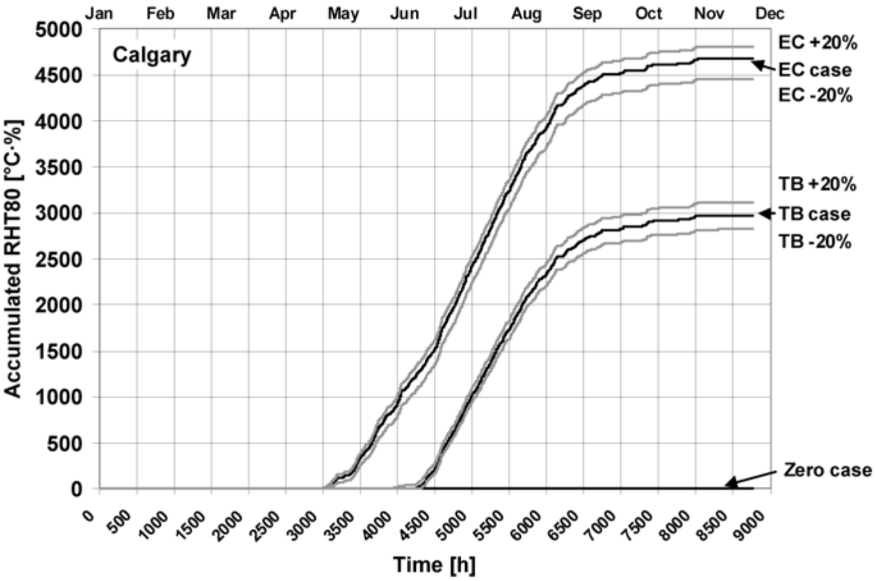

FIGURE 5—Time series of accumulated RHT80 for the parametric variations for Calgary AB. For each set of cases (EC and TB black lines) all the parametric variations are within the 20 % boundaries (grey bands). Note that the RHT80 Index was zero for the ZC variation.

Two distinct curve groupings are apparent from the figures. This is the result of the pattern of rainfall in the tipping bucket cases (TB) being different than the rainfall pattern derived from the weather observation codes (EC). The difference in rainfall pattern for Calgary can be seen in FIGURE 2. Generally one notes deviations from the climate normal data in the tipping bucket amounts in spring and fall seasons in cold climates. Consequently the tipping bucket data sometime record more or fewer events than the files generated from observer codes [15]. In other locations where the temperatures are warmer the tipping buckets can operate all year and the TB and EC cases tend to be synchronized in terms of events.

Instead of analyzing and presenting a multiplicity of graphs the results were summarized by calculating the Mean Bias Error (MBE) for the mould index and moisture content and calculating the accumulated RHT80 index at the end of the simulation period. FIGURE 6, FIGURE 7, and FIGURE 8 show the change in response due to a change in applied rain. The TB case is used as a reference. Change in rainfall is expressed as the ratio of rainfall striking the wall to the rainfall striking the wall in the TB case. The change in MC and MI was defined as the MBE for the TB case. The absolute change in accumulated RHT80 was used to distinguish between the cases as well. Three locations are shown representing three different climate zones represented in the study: mixed marine, cold humid, and very cold dry. The climate zone definitions are from the 2006 International Energy Conservation Code [34].

DISCUSSION

First, it is apparent from the figures that the response to variation in rainfall amounts is similar regardless of the response measure used. Second, the response curves are similar for different locations. The main differences between the curves are due to climate. In all climates large changes occur from the zero case to the first case rain variation, the TB-20 case. For the mixed marine climate, however, the response is somewhat insensitive to changes in rainfall around the TB case, changes of over 100 % produce changes in MC of less than 2 %. For these types of climates it would appear that walls modeled in the manner prescribed by Standard 160-2009 produce high moisture levels at the point of focus. Measures that use RH as a parameter, RHT80 and MI, become insensitive at high levels of RH due to the exponential nature of absorption isotherm. These can be seen clearly in FIGURE 7 and FIGURE 8 for the mixed marine climate. A similar effect occurs for the cold humid climate. Very cold dry climates are more sensitive to changes in rainfall; however, the trend flattens with increasing rainfall.

The sensitivity is determined largely by the local climate, especially the relative humidity. This determined the initial conditions, which for the marine climates were above 80 %. This explains the large variations from the zero case to the first variation, TB-20. The dry climates showed a similar trend but there was still some sensitivity around the TB case. The results suggest that for this type of wall, using Standard 160-2009 as the basis, the variations due to uncertainties in the rain data tend to be less than the variation in the rain data or they become flat.

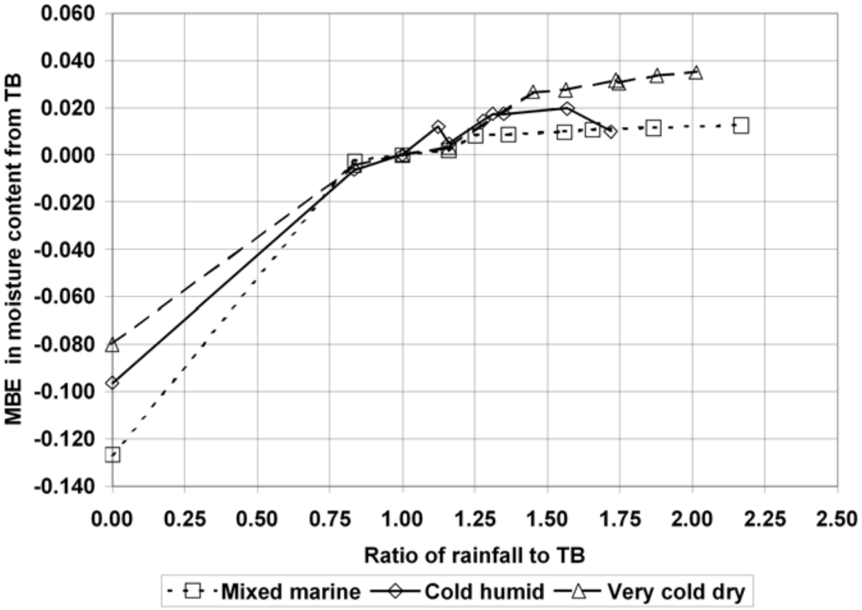

FIGURE 6—Changes in moisture content due to variations in rainfall.

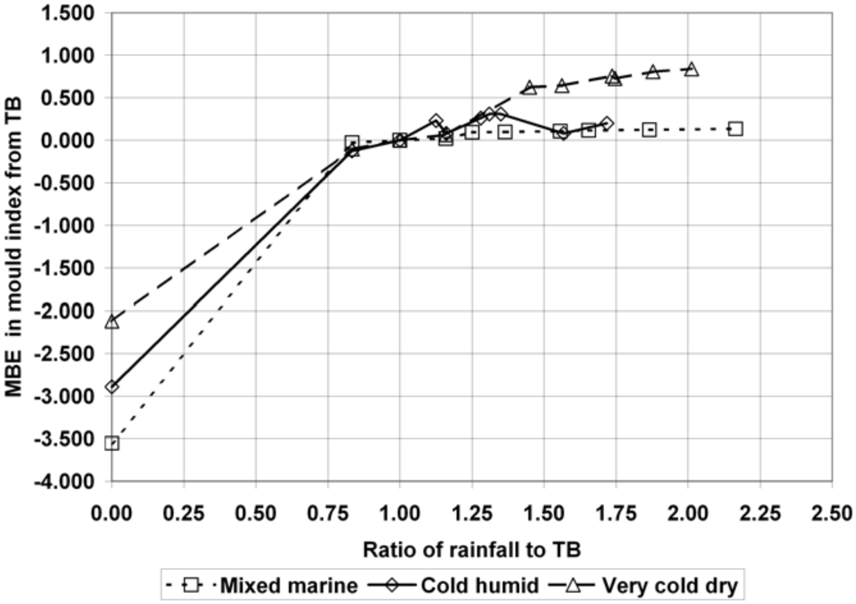

FIGURE 7—Changes in mould index due to variations in rainfall.

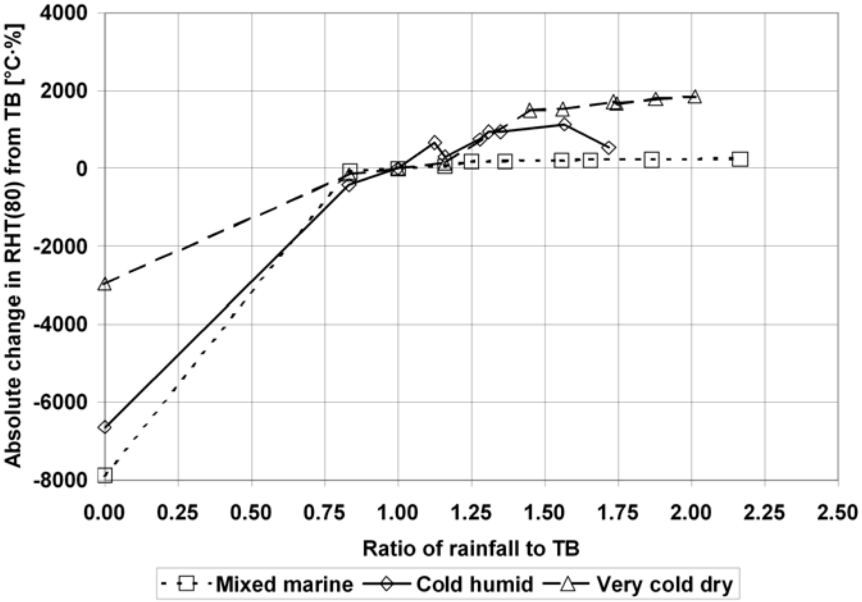

FIGURE 8—Changes in accumulated RHT80 due to variations in rainfall.

The results of the MEWS study showed similar results [24]. In this study four major wall types were considered: stucco-, EIFS-, brick-clad, and wall clad with siding. The major differences were (1) the placement of “leaked” water was at the exterior bottom portion of the stud cavity; (2) the rainfall was not varied but rather the amount of water entry was varied; (3) the amount of water entry was dependent on the wall type and the pressure difference across the wall as well as rainfall; (4) RHT95 was used as an indicator; and (5) a two-dimensional hygrothermal model was used. The amount of water entry was in the range of 3–4 % of the amount of water striking the wall, except for the brick-clad wall, which was in the 1–2 % range. By reprocessing some of the data from this study it was possible to compare the trends. FIGURE 9 shows the response of a siding-clad wall with variation in Q. Q is the amount of water entry into the stud-cavity for a given wall type and is a function of rainfall and pressure difference across the wall. Varying Q varies the amount of water in the stud-cavity but not the amount of water striking the wall. In this case Q ranged on average from 3-4% of the water striking the wall. Thus the response at 0.25Q is of interest and can be used as a reference similar to the TB case. In reprocessing the data, Q’ represents the rainfall in the weather file, unvaried, and approximately 1 % of the wind-driven rain is deposited in the cavity. The same trend is apparent for most climates in the MEWS study and the hot dry climates show a similar trend to the very cold dry climates modeled here.

The Matiašovský and Koronthályová [25] and Koronthályová and Matiašovský [23] studies showed that there was very little difference in the hygrothermal response between simulations based on hourly data and simulations based on hourly data constructed from daily data. The walls modeled, however, were massive masonry walls, 300 mm thick, with a considerable buffer capacity. The point of focus was 215 mm deep from the exterior. Model runs using similar heavyweight walls show almost no change in MC at a depth of 215 mm (MBE = 0.0002) between the TB-20 and EC+20 cases. Even at the interface of the concrete and the lime plaster, at 16 mm depth, the change in MC was small (MBE = 0.001).

Varying the rainfall amounts, either by varying the tipping bucket data, or choosing different methods for deriving quantities of water from qualitative codes does cause differences in the response measures investigated. These differences appear to be manageable, but their contribution to uncertainty should be acknowledged. If the amount of rainfall in the data file is assumed correct, especially if the data come from tipping bucket data, it appears that varying the data by plus or minus 20 % does not affect the hygrothermal response by 20 %. FIGURE 10 shows a generalized response curve based on modeling studies of many cases. For the walls studied here for most climates the response is characterized by the flat part of the response curve, past Point B. For drier climates the response lies between Points A and B, the steep portion of the response curve.

Practitioners should show their awareness of uncertainty by stating error bands for their predictions of performance. Establishing these error bands is not a trivial matter. The first problem is establishing which is the correct amount of rainfall. FIGURE 11 shows tipping bucket data and rain code derived data compared with the archived data for Vancouver and Regina. The archive data were obtained from Environment Canada's on-line database of archived weather data. The database includes archived weather data from all sources. For Vancouver the tipping bucket data are close to the archived data whereas for Regina the rain underestimates the archive data by 25 %. Selecting which data are correct in general is not clear. Second, assuming that the correct estimate of rainfall can be obtained it is difficult to estimate the amount that the rainfall amounts should be perturbed. Errors in measuring rainfall occur due to instrumental and meteorological factors [35][36]. Losses due to wind field deformation can range up to 50 % [37]. There is also an issue of just how representative the rain data are of the local conditions [35]. Obtaining an estimate of the measurement error is possible only in the case of detailed investigations for the particular site. One possible solution would be to perturb the rainfall amount by the standard deviation of annual climate normal (long-term) rainfall amounts. The difficultly here is the statistical data on rainfall are not often published. Standard deviations for the cities used in the studies were calculated and are given in TABLE 1. The data confirm the general meteorological rule of thumb that the lower the mean annual rainfall the greater the variability. In percent terms the standards deviations range from 11 % (Vancouver) to 47 % (Iqaluit), with a mean deviation of 22 % from the long-term normal value. It is possible to derive an equation predicting the standard deviation however the benefits do not seem to outweigh any advantages gained. Perturbing the rainfall by plus or minus 20 % should be sufficient to cover errors inheriting in the rainfall measurement, although this amount should be increased proportionally in dry climates (less than 500 mm mean annual rainfall). It might not be possible, however, to perturb the input to the hygrothermal model. In these cases error bands can be estimated from FIGURE 6. If the rainfall data are correct to within 20 %, an error band of plus or minus 5 % (increased proportionally for dry climates) should be assumed on the moisture content curve. An example is shown in FIGURE 12 for Regina, SK. Similar bands could be applied to the MI and RHT80 indices, but since they are derived from temperature and moisture content, this is not necessary. The variation in temperature across all cases was negligible.

Finally it should be noted that the work here focused exclusively on rain. In reality, wind-driven rain is the parameter of interest. Uncertainty in wind data as well as rain data contributes to errors in the amount of rain impinging on the wall. Cornick and Lacasse [38] have approached the problem statistically although the object was to determine wind-driven rain test levels and not wind-driven rain data for hygrothermal modeling. Blocken and Carmeliet [20] have published a large body of work focused on wind-driven rain and they recommend a CFD approach to estimating the amount of water impinging on building surfaces. Although this approach eliminates some of the errors associated with the modeling of wind-driven rain it is still susceptible to errors in input.

CONCLUSIONS

The sources of uncertainty dealt with in this small study are not the only ones. There will always be uncertainty in the climate input data for hygrothermal models. Due to the nature of the phenomenon, rain is perhaps the one climate parameter with the most uncertainty. Since most hygrothermal models require fully populated datasets, modelers are forced to use data with a certain amount of variability. The plan for the work described had two parts: the first part was to examine variability of various methods for fully populating datasets with rainfall given only qualitative data. This work was reported elsewhere. The second part of the work was to determine whether or not the various data filling methods had any effect on the response of hygrothermal models. In all cases the rain gauge data were assumed to be correct. Variations of rain gauge data were also examined.

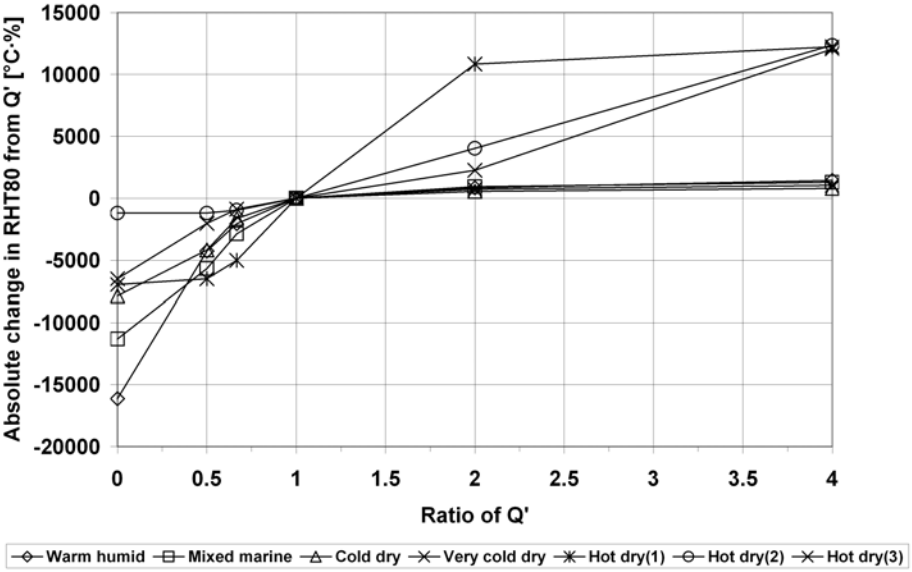

FIGURE 9—Sensitivity RHT80 of a siding-clad wall to changes in water penetration.

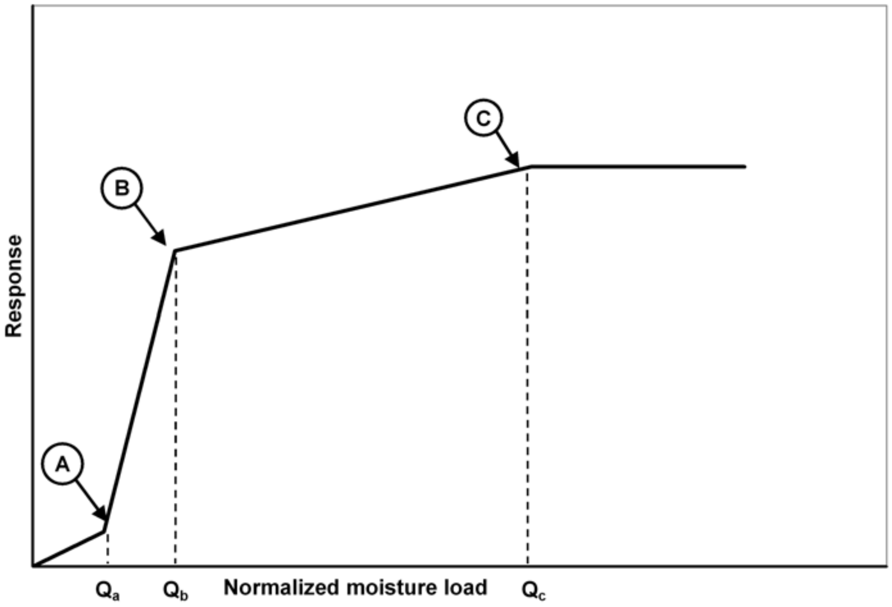

FIGURE 10—Generalized curve of response to changes in moisture load from [24]. Q is the normlaized moisture. Along the x-axis, ratios of Q are plotted.

Although there can be considerable uncertainty in the amount of rainfall in the weather files, the differences in the response measures investigated appear to be manageable. The conclusions of the work are:

- Changes of rainfall around the rain gauge data produced differences in hygrothermal responses. For most cases and climates these differences were small and always less than the change in rainfall. For all but the dry climates the application of the 1 % criterion produced hygrothermal conditions that were in the flatter part of the response curve (beyond Point B, FIGURE 10).

- Investigating other studies and reprocessing or redoing some simulations to verify the results showed the same general trend. The hygrothermal response is somewhat insensitive to changes of rainfall around the rain gauge data values.
- Hot and dry climates are an exception; the response tends to be in the steep part of the generalized response curve. The change is still less than the change in rainfall however.
- The general conclusion is that for most hygrothermal responses uncertainty in rainfall data *around the values available from the weather file* is not a cause for great concern. In most cases the unmodified rain data from the weather and 1 % penetration criteria will produce a response in the flat part of the generalized response curve.
- Practitioners can demonstrate their awareness of the probable level of uncertainty by stating error bands for their predictions of performance.
- When there is reason to suspect, however, that the response will be in the steep region of the generalized response curve, such as in the hot dry climates, perturbing the rainfall data by 20 %, positive and negative, should adequately bracket the response given uncertainty in the rain data.
- If perturbing the input data is not possible an error band of plus or minus 5 %, increased proportionally for dry climates, in the moisture content curve should be assumed
- While the conclusions seem to be valid it must be noted that all the possible combinations of wall configurations were not studied.

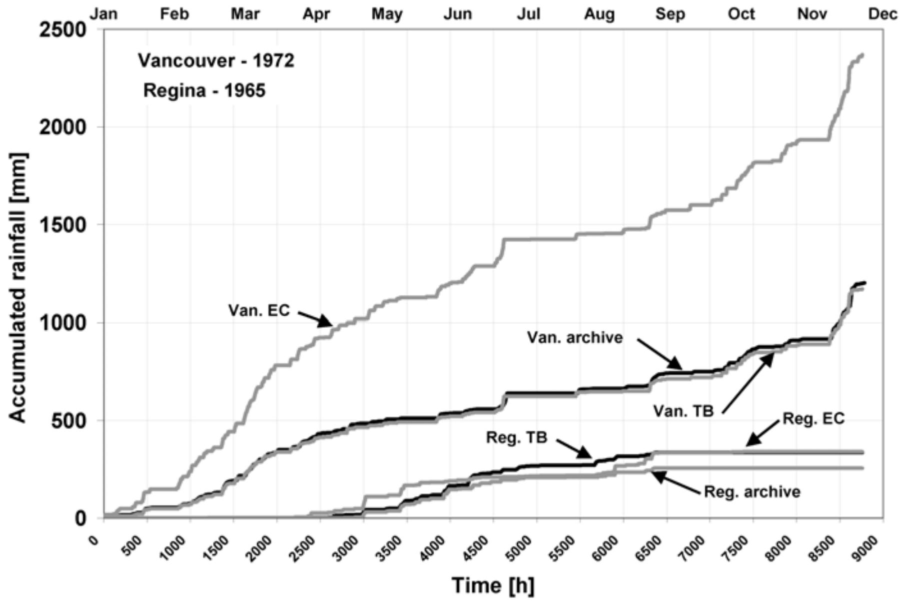

FIGURE 11—Comparsion of archived data with rain gauge data and rainfall estimated from weather observation codes. For Regina SK and Vancouver BC.

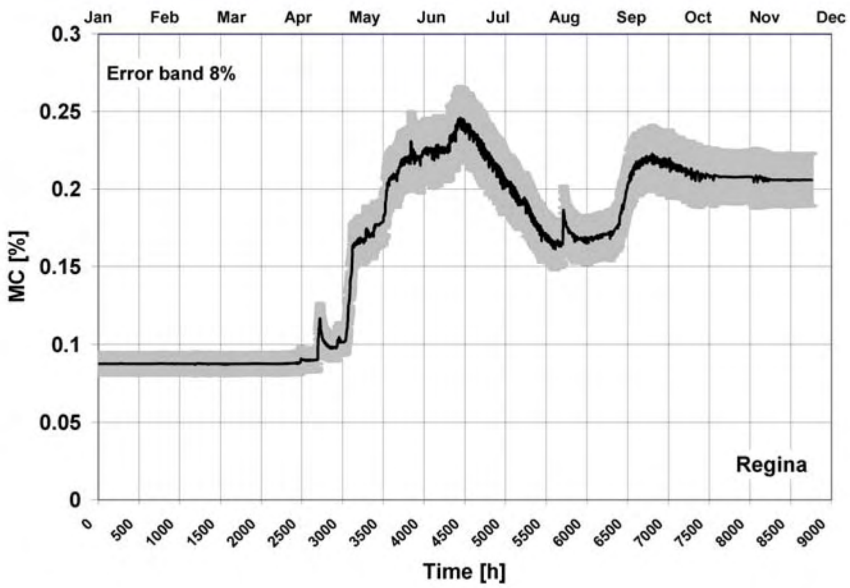

FIGURE 12—An example of proposed errors bands. The error bands were calculated by multiplying the 5 % proposed errror band by the ratio of the dry threshold limit (500 mm) to the mean annual rainfall.

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