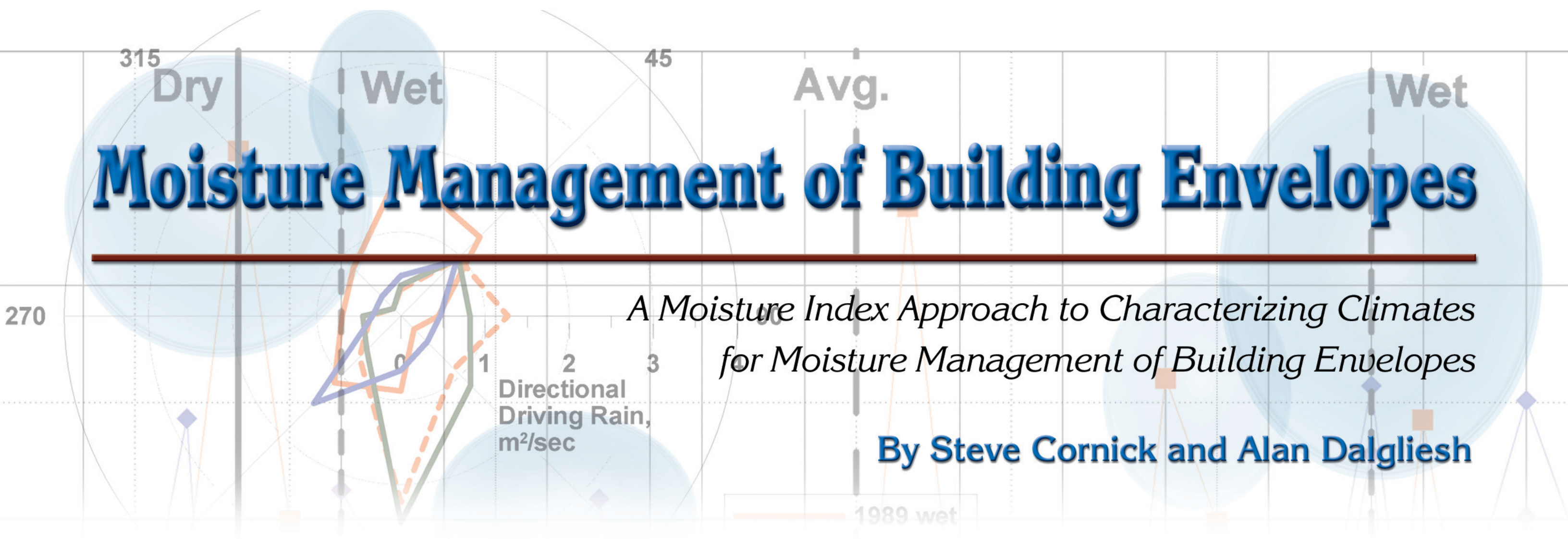


Moisture Management of Building Envelopes

A Moisture Index Approach to Characterizing Climates for Moisture Management of Building Envelopes

By Steve Cornick and Alan Dalgliesh

INTRODUCTION

Recent history has documented the premature failures of building envelopes in various regions of North America – notably on the West Coast and the East Coast [1], [2]. The problem appears, to some extent, to be influenced by climate. The MEWS (Moisture Management of Exterior Wall Systems) Consortium project, undertaken by the Internatonal Research Council of Canada (IRC) and its partners, has addressed this issue in detail. The objective was to develop guidelines for moisture management strategies for wall systems to meet user requirements of long-term performance and durability for the wide range of climate zones across North America [3]. The focus was on wood-frame buildings of four stories or less, exposed to a range of outdoor climates.

Effective moisture control implies both minimizing moisture entry into the system and maximizing the exit of moisture that does enter, so that no component in the system stays "too wet" for "too long." But what is "too wet" and "too long"? The strategy for answering these questions was based on predicting the moisture management performance of wall systems as a function of climate, wall construction, and material properties through mathematical modeling. A large parametric study was undertaken using a state-of-the-art two-dimensional transient heat, air, and moisture transport model [4].

A major task, among others, was to determine, using climatic data, which North American locations require special provisions to mitigate moisture related problems. There are several different schemes for classifying the world's climates. Most of the climate classification schemes have subdivisions and boundaries partly based upon temperature and rainfall parameters, which have significance in terms of some non-climatic feature such as vegetation or human habitability. If one disregards non-climatic phenomena, it is difficult to provide meaningful temperature-rainfall limits of climatic types. The majority of classification schemes, therefore, are of an "applied" character. Traditional climate classifications, although useful, are too coarse to be of use to building science practitioners.

An approach to climate classification based on a Moisture Index was developed. The Moisture Index relates the wetting and drying potential of a climate. A provisional map of North America was produced using the Moisture Index approach, mapping the continent into zones related to potential moisture problems. A key task was to determine which years to use as input for a parametric hygrothermal study of wall systems and climate. Moisture Reference Years were selected using the Moisture Index approach developed. The objective of this paper is to report on the development of the Moisture Index approach, evaluate the measure by comparing it to a hygrothermal response indicator, and give two examples of its application. The first is a case study in producing a moisture risk hazard map, and the second illustrates the selection of Moisture Reference Years for a parametric study using a hygrothermal simulation tool.

A Moisture Index for Building Envelopes

There exist several maps to help designers and builders. Some, such as Lstiburek's [5] and Russo's [6], are based on combinations of temperature and rainfall that are of particular concern to designers and builders. Other maps, such as Boyd's [7] are based on wind-driven rain and are used

EQUATION 1:

$$\Delta w(h) = w_{saturation}(hourly_{temperature}) - w_{out}(hourly_{temperature})\ \text{kg water/kg air}$$

EQUATION 2:

$$DI = (1/n) \sum_{i=1}^{n} \sum_{h=1}^{k} \Delta w(h)\ \text{kg water/kg air-year}$$

Where: DI is the Drying Index in kg water/kg air-year
n is the number of years under consideration, and
k is the number of hours in a particular year.

EQUATION 3:

$$MI = WI/DI$$

EQUATION 4:

$$MI_{mews} = \sqrt{WI^2_{normalized} + (1 - DI_{normalized})^2}$$

with respect to durability issues. Maps such as Setliff's [8] explicitly characterize climate with respect to the risk of decay in exterior wood in above-ground structures.

Another approach to climate classification is based on defining a Moisture Index. Bailey [9] provides a succinct definition of a Moisture Index. A Moisture Index compares wetting and drying, or more specifically, evaporation. Moisture Indices have an established history in climate zoning for such applications as agriculture and vegetation in general. Drying can be a significant factor when assessing the required level of protection for walls exposed to rainfall, making the Moisture Index potentially preferable to construction-related temperature-rainfall approaches to climate zoning. In the most general form, a Moisture Index can be written as a function of a wetting component and a drying component.

The wetting component might be defined by one of the following measures or functions of wetting: annual or annual directional, Driving-Rain Index (m^2/s-year), average annual rain load on a wall, or rainfall on the ground (kg/m^2-year). Ideally, a comparative index of wetting should measure the amount of water that a wall system must manage by deflecting, draining, or drying. On the other hand, there is some merit in staying independent of the wall construction and in choosing the simplest and most readily available measure. Thus, unless otherwise indicated, the Wetting Index (WI) is the average annual rainfall on the ground (kg/m^2-year).

Setting aside deflection and drainage as attributes of wall construction, we are left with drying as the other component of MI. Measuring drying is a little more complex than using rainfall for the wetting component (see the MEWS Task 4 Final Report [10]). A simple measure of drying that relates to evaporation is the difference between the humidity ratio at saturation and the humidity ratio of the ambient air. This is a measure of the capacity of the air to take up water vapor, calculated from the dry bulb temperature and relative humidity. This is similar to the ∏ factor method described by Hagentoft [11]. Unlike the ∏ factor method, however, the drying function does not use the assumed characteristics of the wall. The Drying Index at time *t* is simply the difference between the humidity ratio (alternatively the mixing ratio) at saturation, $w_{saturation}$, and the humidity ratio at ambient conditions, w_{out} (*Equation 1*). The Drying Index for a location can be calculated from *Equation 2*.

The next step is to combine WI and DI into a Moisture Index MI, a single measure of climate severity (from the standpoint of moisture management of a wall system). Perhaps the simplest option is to divide WI by DI, so that a higher number always indicates a greater moisture load:

MI - WI/DI

For comparative measures, it is convenient to normalize the index and to eliminate or ignore units, particularly as they are different for WI and DI. For instance, in comparing MI for a given set of locations, each value can be normalized, or scaled, by dividing by the largest MI in the set.

Another option for MI, which was in fact used in the MEWS implementation, requires WI and DI to be scaled to lie between 0 and 1 for the set of locations being compared, before they are combined as shown in *Equation 4*. MI_{mews}, therefore, has a theoretical maximum value of 1.4

Figure 1 shows the west to east progression of the two versions of Moisture Index for several major Canadian cities. The hypothesis is that the higher the value of MI, the greater the potential risk for moisture-related damage. The values for WI/DI have been normalized to the maximum value in the data set, St John's NF, which has a "raw" MI of 1.17. A clear distinction is made between the coastal and continental climates. Lower values are apparent in more continental locations.

The normalization of MI_{mews} took into account a much larger set of North American climates. If the range of WI and DI is changed significantly, a different ranking will result. The west to east progression of MI_{mews} for the 13 Canadian cities is similar to the simple ratio definition but, due to the different normalizing scheme and a larger sample set size, the relative magnitudes of the two measures differ.

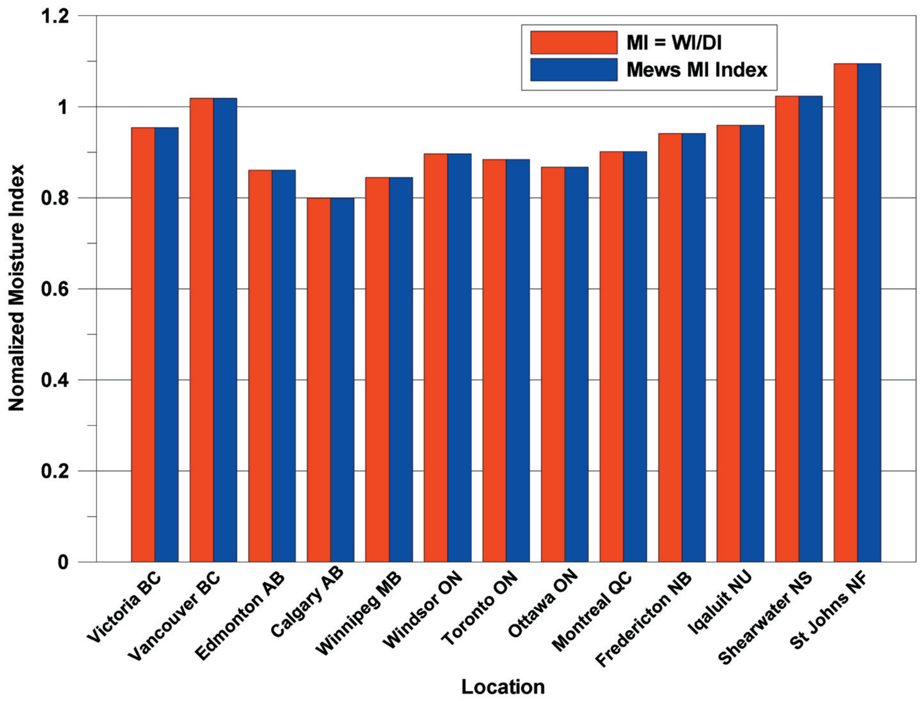


Figure 1: West to east progression of MI and MI_{mews} for several Canadian cities.

What arguments can be given in favor of the more complex definition of MI? If one thinks of wetting and drying as the balancing of a moisture budget for the wall system, there may be a preference for MI_{mews}. It can also be pictured as the distance from the origin of an x-y plot of one minus the normalized DI versus the normalized WI, *Equation 4*. Severity of the Wetting Index increases from zero to one. The severity for one minus the Drying Index also increases from zero to one. The potential for moisture problems increases with increasing values of x and y. A point near the origin (0, 0), consequently would have the lowest potential for moisture-related problems while the point furthest from the origin (1,1) would have the highest.

The MI_{mews} for each city in the sample set was calculated as the distance from the origin. This is shown in *Figure 2*. The moisture indices for 41 candidate cities were calculated from hourly data. The cities were selected to represent the range of interest of the MEWS partners. Out of these 41 locations, seven were selected for the paramet-

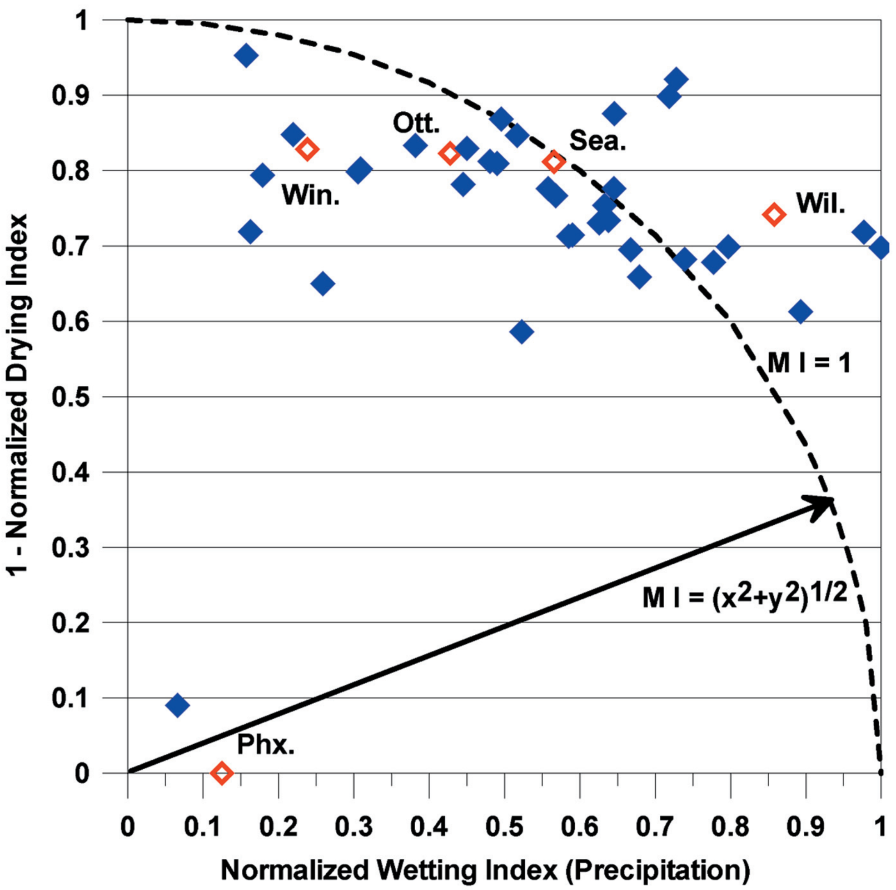


Figure 2: A plot of 1 - normalized Drying Index versus normalized Wetting Index.

Location	Main Driving-Rain Direction	Climate Type (Russo) [6]	Lstiburek [5]	Rank, MI_{mews}
Wilmington, NC	North	Hot, Wet	Mixed Humid	1.13
Seattle, WA	South	Mild, Wet	Cold	0.99
Ottawa, ON	East	Cold, Wet	Severe Cold	0.93
Winnipeg, MB	North	Cold, Dry	Severe Cold	0.86
San Diego, CA	South	Hot, Dry	Hot Dry	0.74
Fresno, CA	East	Hot, Dry	Mixed Dry	0.49
Phoenix, AZ	East	Hot, Dry	Hot Dry	0.13

Table 1: Moisture indices for the seven representative cities chosen for parametric study.

ric study. Two cities from the top third of the ranked list, two from the middle third, and three from the bottom third of the list were selected for more in-depth analysis. The seven locations chosen for detailed analysis are given in *Table 1* as well as the range of climate types covered by the selected locations.

The approach used in the MEWS project, which was to define the Wetting Index using annual average rainfall, has two advantages. First, developing wetting indices from annual rainfall is more practical and the data are readily available. Considerably less time and fewer resources are involved compared to generating these values from hourly concurrent rain and directional wind data. The Moisture Index can be reduced to three elements: temperature, humidity, and rainfall. This approach can also be applied where hourly data are not available. This is shown in the section describing the development of a provisional map. Second, the normalization scheme can help to set quantifiable limits on the MI_{mews} that can be used for climate zoning.

Relationship Between Hygrothermal Response and Moisture Index

The ultimate test of a Moisture Index is its success as an indicator of climate severity with respect to the potential for moisture-related damage. Recall that the hypothesis is that the higher the value of MI, the greater the potential risk for moisture-related damage. *Figure 3* shows the relationship between the Moisture Index for the seven cities considered and a proposed wall response measure known as "RHT," for a wood-framed, stucco-clad wall with OSB sheathing.

Wall Response

The definition of this wall response measure is provided in the MEWS summary findings report [3], but a brief description of RHT geared to wood decay is as follows.

Fungal attack of wood-based materials in a wall requires sustained conditions of high moisture content combined with above-zero temperatures. Hence, a single-numbered indicator RHT is formed by multiplying ($RH - RH_{threshold}$) by ($T - T_{threshold}$) and summing only non-zero values for two years for a target region in the wall. The target region for the wall in *Figure 3* was a thin lamina of wood at the top of the base plate inside the insulation cavity. Relative humidity of the wood is determined from the moisture content of the wood and calculated using a sorption isotherm. For the study, the RH (relative humidity) threshold was 95%, and the T (temperature) threshold was 5°C. The thresholds are an estimate of the limiting conditions for the onset of wood decay. For other types of moisture damage, different thresholds could be used, e.g., 5°C and 80% RH for mold; 0°C and 95% RH for corrosion. The hypothesis here is that the higher the value of RHT (95), the higher the likelihood of the onset of wood decay.

Wall Response versus MI

In *Figure 3*, increasing climate severity (MI) is measured along the x-axis, while the increasing risk of moisture-related damage (RHT) is measured along the y-axis. The figure shows three curves. The lowest curve (blue) shows the response of a wall without water ingress; and the top curve (red), the response of a reference wall with water ingress through a deficiency. The middle curve (green) shows the response of wall with water ingress but with materials chosen to promote drying to the exterior.

Details pertaining to the construction of the wall, choice of materials, amount of location of water entry, and air leakage are discussed at length in the summary findings of the MEWS project [3]. When there is

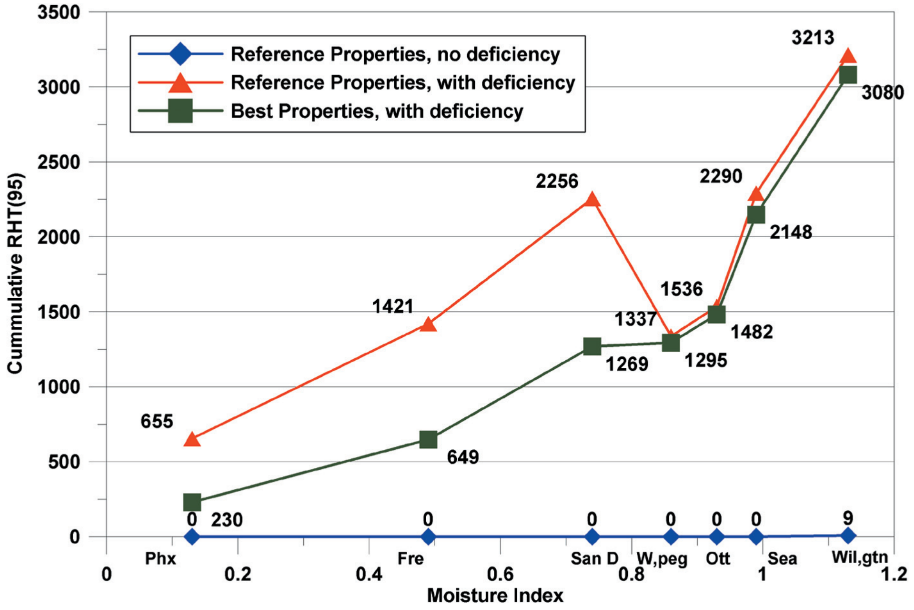


Figure 3: The relationship between climate severity and wall response for 3 scenarios.

Division	Classification w.r.t. Moisture Problems	Color
MI greater or equal to 1.0	Severe	🟥
MI greater or equal to 0.9 but less than 1.0	High	🟧
MI greater or equal to 0.8 but less than 0.9	Moderate	🟨
MI greater or equal to 0.7 but less than .0.8	Limited	🟩
MI less than 0.70	Low	🟦

Table 2: Proposed climate classification scheme used to make the provisional map.

no water ingress, there is little or no risk of moisture-related damage. However, if water ingress occurs, the general trend is clear. The response of the wall to water ingress increases non-linearly with increasing climate severity (i.e., MI). *Figure 3* suggests a good fit between MI_{mews} and wall response indicator. There is, however, an outlying point shown in the figure. The explanation of this anomaly rests with the nature of the wall response measure and the temperature regime of the climate in question – San Diego. This is discussed in detail in the summary findings of the MEWS project [3].

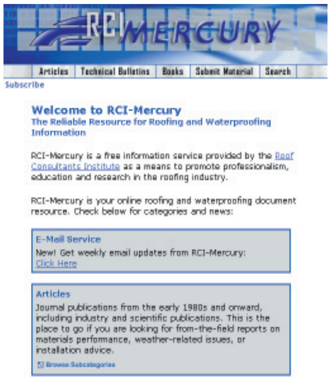
A partial explanation hinges on the interplay of RH and T, whereby the hot-dry climate of San Diego produces nearly the same RHT as the mild-wet climate of Seattle. In San Diego, the RHT accumulation is contingent on occasional periods of high RH, since the T threshold is always exceeded, whereas in Seattle, the reverse is true. The definition of MI_{mews} appears unable to reveal the equivalence in terms of the RHT criteria, but we should observe that a change in materials (the middle curve) improves drying and lowers RH to such an extent that the anomaly disappears. This underscores the difficulty of correlating hygrothermal response of specific wall systems with any MI that is independent of construction details. However, that being said, *Figure 3* indicates that MI as a measure of climate severity is directly related to the risk of moisture-related damage, as it should be.

APPLICATIONS OF MI

A Provisional Climate Zoning Map

Having established the Moisture Index as a procedure for ranking climates, it is possible to establish a method of grouping like climates with respect to potential moisture-related problems. Each grouping can be shown as a zone on a map of North America. Since the MI for a location is defined as the distance that the location's climate WI, 1-DI coordinates lie from the origin on a normalized plot (see *Figure 2*), the boundary values for the groupings can be expressed as radii.

Suppose a particular location has a normalized Wetting Index, $WI_{normalized}$, of one, indicating maximum wetting potential, and a normalized Drying Index, $DI_{normalized}$, of one,



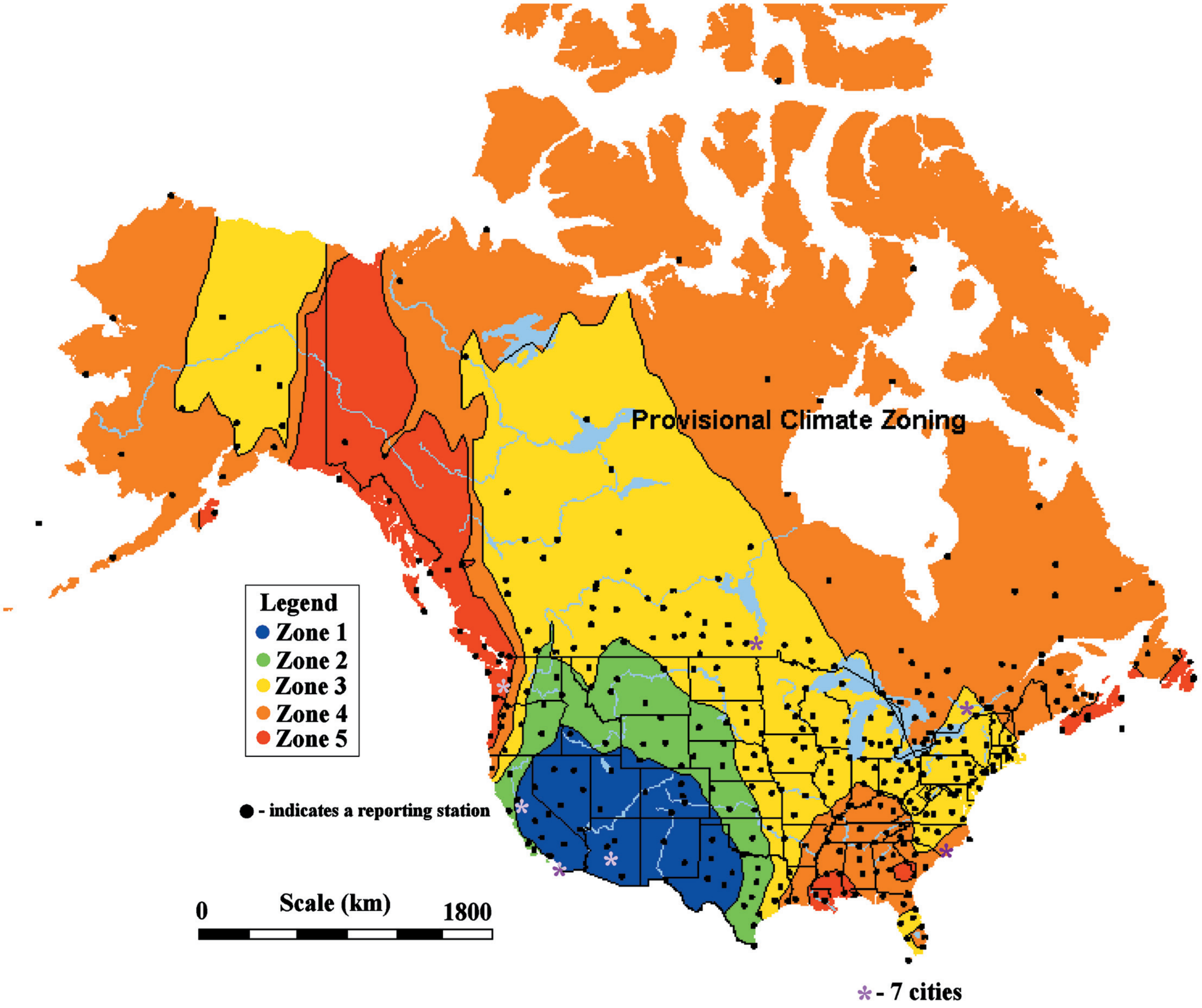


Figure 4: A climate zone map for Canada and the USA.

indicating maximum drying potential. This climate corresponds to the point (1, 0) on the plot shown in *Figure 2*. Note that 1 – $DI_{normalized}$ rather the $DI_{normalized}$ – is plotted on the y-axis. This ranking corresponds to a radius, *r*, equal to one. Similarly, a climate having $WI_{normalized} = 0$, minimum wetting, and $DI_{normalized} = 0$, minimum drying, corresponds to the point (0, 1) in *Figure 2*. This climate also lies on the arc $r = 1$. Although both these climates might differ in terms of wetting (rainfall) and drying (difference in humidity ratios) characteristics, the hypothesis is that they are similar with respect to the potential for moisture-related problems. Using an analogy to Mohr's circle, the climates represented by points along a radius are hypothesized to have an equal (iso-) potential for moisture related problems. A simple classification can be constructed by splitting the range of MI into a number of divisions. Each division represents a limit for moisture-related problems. Climates are then grouped accordingly. A possible climate classification is given in *Table 2*.

Figure 4 was constructed using 383 stations reporting hourly data. The rankings for each station were calculated using long-term data, temperature, RH, and rainfall, obtained from climate normals. The current climate normals span the years 1961 to 1990. The Wetting Index was defined, as before, as the annual average rainfall. The Drying Index was computed using the method described except that the average annual temperature and average annual relative humidity were used instead of hourly values. A method to determine MI from climate data was developed and reported on by Cornick [10]. The method makes use of average annual values to reduce the calculation effort; the results correlate well with those of the hourly method.

A few comments on the provisional contour map are worth mentioning. First, in generating a contour map, a certain amount of information is lost. Second, the network of reporting stations used to generate the map is sparse in the northern regions of the continent. Third, the selection of the MI

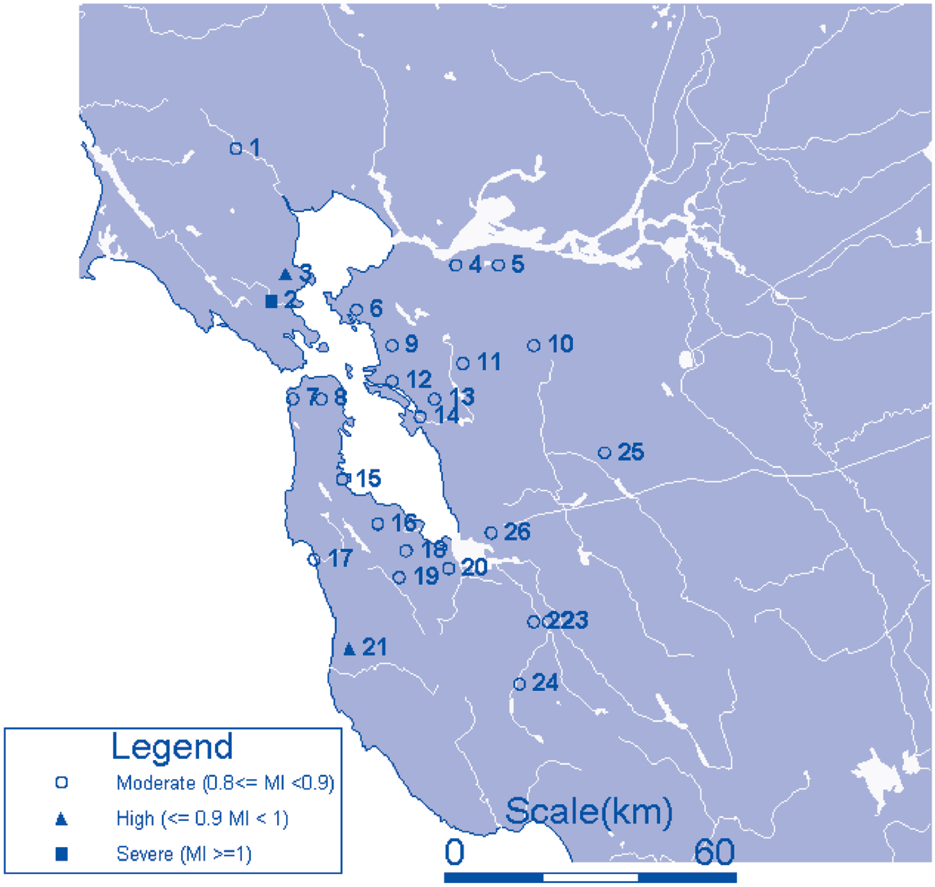


Figure 5: MI values for 26 stations in the San Francisco Bay area. The airport is labeled 15.

defining limits to various climates regions is not related to experimentally observed data, but rather anecdotal data (e.g., real experience).

Application of the Methodology to Local and Micro Climates

The Moisture Index methodology was developed on a macroclimate scale. Hourly and climate normal data (generally from reporting stations at or near airports) were used in the development and application. Local and meso-climates can have a marked effect, however, on the values of MI. The west coast of North America features many examples of local climates that vary markedly over short distances. The Vancouver, Seattle, and San Francisco Bay areas are notable examples. These local climates feature a small coastal littoral backed by mountains and a cold ocean current. Orographic lifting of air on the windward side of the coastal mountains causes increased precipitation with increased elevation on the windward slopes and a rain shadow forms on the leeward sides of the coastal mountains. The MI value for San Francisco, for example is 0.86, in the moderate category defined in *Table 2*. Is this representative of the San Francisco Bay area? The answer is yes and no.

The MI methodology can be applied to local as well as macro-climates. Like maps showing elevation contours, the scale of the analysis and mapping needs to be adjusted to suit the purpose. If enough data are available, then small-scale studies can be done. The Bay Area, for example, has at least 26 stations reporting temperature and rainfall. The variation in annual average temperature is around 3.3°C. Although this might not seem like much, the difference in average annual temperature between Vancouver, BC and Ottawa, ON (two distinctly different climates) is only 4°C. The annual range reveals more, however. The annual range for the Bay Area ranges from 5°C to 14°C. The mean range of the reporting stations in the Bay Area is about 10°C, while the annual ranges for Vancouver and Ottawa are 14°C and 32°C respectively. Temperature in the Bay Area is not the determining factor for calculating MI. Similarly, the variation in relative humidity is not significant with respect to the Drying Index. The Drying Index in and around San Francisco ranges from 0.15 to 0.19 when normalized (divided by the value for Phoenix of 124.6). The variation in rainfall in the Bay Area, however, paints a different picture. Climate normal data from the Bay Area reporting stations show a range in average rainfall of about 880 mm.

Applying the MI methodology to the San Francisco Bay Area using the annual data provided by the local reporting stations, shows most of the stations are in the same risk category as the airport reporting station. Two stations (#3 San Rafael Civic Center and #21 San Gregorio 2 SE), however, are promoted into the high-risk category, and one station into the severe risk category (#2 Kentfield). A map of the Bay Area is shown in *Figure 5*. Airport data are generally representative of large areas and useful for large-scale studies. However, in an area where considerable variation is known to occur (especially in rainfall), airport data are not appropriate. Fortunately, the MI method can be easily applied on a local scale if sufficient data are available or reasonable approximations can be made.

Selecting Moisture Reference Years

The International Energy Agency (IEA) Annex 24 on heat, air, and moisture transport, Task 2 Environmental Conditions, has made recommendations on how to determine a moisture design year [12]. Some of the methods require the use of specific building and wall characteristics. The approach taken in the MEWS project was that the climate data would be analyzed independently of the wall response. Consequently, many of the IEA recommendations did not serve the purposes of this project. The approach taken to selecting weather for hygrothermal modeling was to construct input files spanning three years using actual weather data. Using the Moisture Index, it is possible to classify individual years as "wet," "dry," or "average."

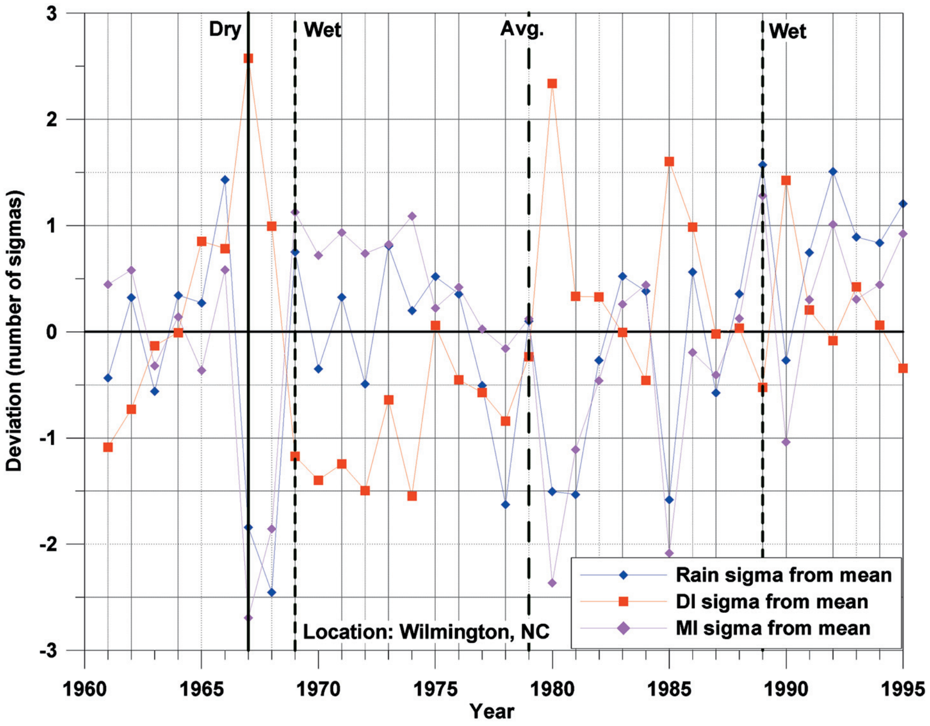


Figure 6: A plot showing the deviations of WI and DI for individual years from the mean.

For a particular city, the Moisture Index for each year was calculated, the hypothesis being that the higher the Moisture Index, the greater the potential for moisture loading. “Wet” and “dry” years were defined as those years that deviate more than one standard deviation from the mean MI value of the sample set for a city. “Average” years were defined as being within one standard deviation of the mean. The “wet” year for a city was defined as the year with the highest Moisture Index, the “dry” year as the year with the lowest Moisture Index, and the “average” year as the year closest to the mean Moisture Index.

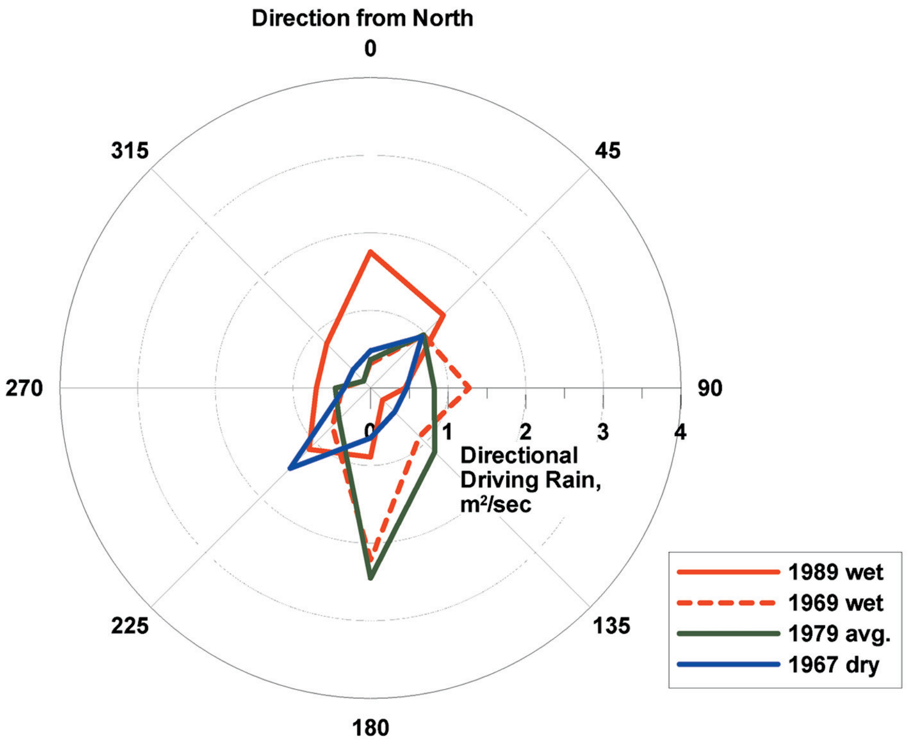
Figure 6 shows three years selected as “wet,” “dry,” and “average” for Wilmington, North Carolina. The chart shows the deviation of the Moisture, Drying, and Wetting indices from the mean in terms of standard deviations, σ. Years selected as “wet,” “dry,” and “average” are highlighted. The dry year can be seen to have a higher than normal Drying Index and a lower than normal Wetting Index. The combination produces the lowest Moisture Index. The wet year is a combination of low DI and high WI producing the highest value of MI. Average years lie close to the mean MI.

ORIENTATION AND PREDOMINATE DIRECTION

Up to this point, the Drying Index and wetting indices have been developed without considering building orientation. This was in keeping with the *a priori* decision that climate would be treated independently of the wall or building. Recall that the Wetting Index was defined as the annual rainfall on the horizontal. The scope of the MEWS parametric study phase, however, was limited to analyzing one wall orientation. This required a modification of WI. Why?

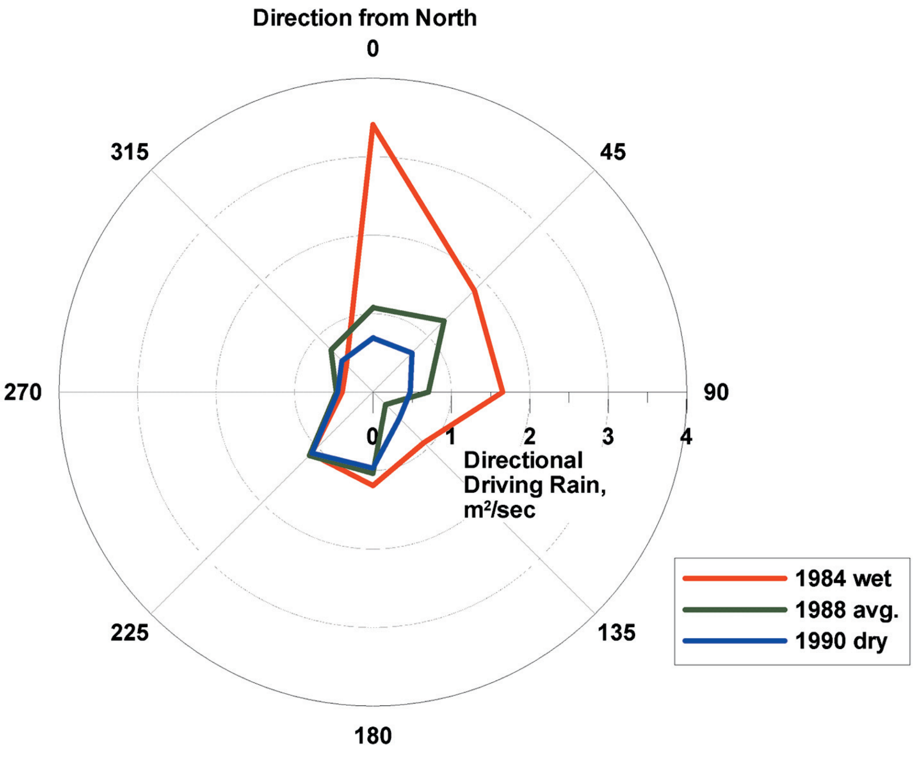
Figure 7a shows directional driving rain indices (dDRI) for two “wet” years, an “average year,” and a “dry” year, selected from the Wilmington, NC weather record. In the Moisture Index used for selection, WI was equal to the annual rainfall on the horizontal. Suppose that the orientation of a given wall is south. The hygrothermal model will impose a rain load on the wall in proportion to the wind speed, wind direction, and rain intensity. A south-facing wall will see more rain during the “average” year than during both “wet” years. If one wished to compare the wall response to the “wet” year 1989 with the dry year 1968, a north or northeast orientation would be preferable.

Clearly, WI must take direction into account if only one wall orientation were to



(a)

Figure 7a: Four years classified as "wet," "average," and "dry" using rainfall as the WI.



(b)

Figure 7b: Three years classified as "wet," "average," and "dry" using directional driving-rain as the WI.

be considered. To include the effect of orientation on wind-driven rain, a modified Wetting Index was based on a method recommended by Straube [13][10]. The first step in introducing a directional component was to determine the predominant direction of rainfall as it relates to wind speed and direction. The rain impinging on the wall was calculated for all the years available. The rain load on the wall was calculated for the four cardinal orientations for each city. The direction with highest amount of total rain impinging on the wall was selected as the predominant direction for rainfall. Instead of using the rainfall for the year as the wetting component for that year's MI, the wetting component is now calculated as the amount of water impinging on a wall in the predominant direction. The years selected for the hygrothermal model as "wet," "dry," and "average" for Wilmington, NC are shown in *Figure 7b*. Note that the selection of the Moisture Reference Years when compared with those shown in *Figure 7a* now show a bias towards wetting in the direction of predominate rainfall.

CONCLUDING REMARKS

For the purposes of characterizing moisture-related problems in building envelopes, climate can be described by a Moisture Index that combines two independent indices, a Wetting Index (rainfall), and a Drying Index (potential evaporation). The MI can then be used to rank weather stations in a climate classification scheme. Increasing concerns for adequate moisture-related performance of wall cladding systems have heightened interest in hygrothermal models. This, in turn, drives the need for appropriate Moisture Reference Years to be used as input for model studies. To select appropriate MRYs, it is desirable to classify weather years according to criteria relevant for the problem at hand. As just one example, sequences of years can be assembled to deal with problems such as long-term performance or limit-state design – i.e., recurrence of years that severely stress the wall assembly. There is probably no one definitive set of MRYs that is appropriate to solve all the hygrothermal problems of interest. Similarly, there exists no definitive method for selecting MRYs. Different sets of MRYs should be produced to suit different problems.

The MEWS Moisture Index offers several desirable features for hygrothermal modeling:

1) It characterizes years statistically, e.g., to select sequences of years for climate input.
2) Wetting and drying functions can be tailored for specific problems of interest as can the relationship between wetting and drying.
3) MI is quick and easy to implement and calculate, given adequate climate data.

The provisional map showing five climate zones of MI, labelled "low" to "severe," should be viewed with caution. Local areas with rapid changes in MI will require special treatment on a smaller scale, and more importantly, MI alone should be considered as only an initial warning of potential moisture-related problems in building envelopes. MI as defined occasionally fails to rank the hygrothermal responses of certain wall systems correctly according to climate. It is unlikely that any construction-independent MI will escape the necessity of confirmation by hygrothermal modelling or case studies of actual wall systems. Finally, confidence in hygrothermal modeling itself depends on validation by well-controlled laboratory experiments, such as those done by MEWS, as well as well-documented field experiments.

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MEWS is a joint research project between IRC-NRC Canada and several external partners. More information about the MEWS project can be obtained from the Institute for Research in Construction.

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Construction Growth Carried by Housing

Residential construction in the U.S. showed a 20% increase in the first six months of 2004, accounting for 57% of all construction during that period, according to McGraw-Hill Construction. This allowed for a 10% increase over construction for the same period in 2003, it was reported. The nonresidential market was down 1% from 2003. ***— ENR***