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# Meta-analysis based predictions of flood insurance and flood vulnerability patterns in Calgary, Alberta

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ABSTRACT

Flood risk management requires an understanding of the role that the private insurance system can play in helping to manage future flood risk, and how insurance uptake may vary for different levels of social and physical vulnerability to floods. The objective of this research is to understand the patterns of flood risk, socio-economic characteristics and flood insurance uptake in the City of Calgary, Alberta, Canada, where a recent flood was followed by the introduction of private overland flood insurance. We use a meta-analysis approach to generate a pooled prediction of flood insurance uptake, and compare uptake across socioeconomic factors and flood hazard levels. Our results suggest that highest hazard areas have higher household income, higher average dwelling values and lower levels of home ownership compared to other areas in the city. Hazard levels vary less across measures of immigration status and identification as a visible minority. Predicted insurance coverage varies across the city, with households in high hazard areas most likely to purchase insurance, particularly for a pricing scheme in which low risk households cross-subsidize premiums for high risk households. Our findings provide an important starting point for understanding the role of private flood insurance on the future impacts of flooding in the study area, and may serve as a useful template for understanding the impact of insurance in other new markets.

## 1. Introduction and background

### 1.1. Introduction

Floods are the world's most common weather-related natural disaster (Wahlstrom & Guha-Sapir, 2015), and are a growing concern in many parts of the world as a result of anticipated changes to the global climate. In addition to large-scale engineering projects that can reduce flood risk near flood zones, there is a breadth of small scale mitigation tools available as well. These include landscaping, raising houses, and the installation of sump-pumps and/or sewage valves. However, financial cost, lack of public infrastructure and lack of awareness result in a population that is thought to be largely under-protected from flooding in many parts of the world.

The general objective of this research is to understand geographic and socioeconomic variations in flood hazard and uptake of flood insurance in Calgary, Alberta, Canada. In 2013, the City of Calgary and its surrounding area experienced a flood event that resulted in one of the most costly natural disasters in Canadian history with total losses of approximately 6 billion dollars (Gober & Wheater, 2015). At the time, overland flood insurance was not generally available in Canada, however, a number of insurance companies have since begun to offer insurance products to households. The impacts of this very new insurance marketplace on future government disaster relief and population vulnerability to floods are unknown.

Our analysis has three specific objectives that help address some of this uncertainty. First, we describe the socioeconomic characteristics of the population based on exposure to flood risk. Second, we predict and map the spatial variation in insurance uptake in Calgary. Finally, we describe the relationships between predicted insurance uptake and selected socioeconomic characteristics of the population. Given the lack of data and newness of the overland flood insurance market in Canada, we use a meta-analysis approach to make predictions required for our analysis. As such, we also demonstrate a simple methodological strategy for using previous research to understand the impact of insurance on flood vulnerability in settings with no previous history of flood insurance.

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### 1.2. Flood insurance demand

Flood insurance has three key purposes: 1) it internalizes the costs of living in and otherwise using flood prone areas 2) it helps ration and prioritize public flood prevention investments and 3) it covers losses that cannot be protected against by other means (Chivers & Flores, 2002). The availability and regulation of flood insurance varies internationally. In the United States, the National Flood Insurance Program (NFIP) helps underwrite the cost of insurance in some communities, and requires the purchase of insurance for some homeowners with federally backed mortgages. In the United Kingdom, privately underwritten insurance is widely available and mandatory for mortgage holders (Surminski & Eldridge, 2015). In continental Europe, there is a mix of private optional, mandatory, and public disaster relief programs (Bouwer, Huitema, & Aerts, 2007, p. 33). Flood insurance (and natural disaster insurance in general) is less common in low and middle income countries due to their higher susceptibility and vulnerability to extreme weather events, lack of information, lack of public resources to reduce risk, affordability and a lack of access to international insurance and finance markets (Skees, Barnett, & Murphy, 2008).

Economic models of optimal insurance coverage (Smith, 1968) and models of insurance demand (Ehrlich & Becker, 1972) lay the groundwork for the theoretical understanding of private insurance markets. These models have been used to understand the flood insurance market, and to predict household demand for insurance. Alternatives to insurance include self-insurance—lowering the magnitude of potential losses—and self-protection—lowering the probability that a loss occurs may impact demand for market insurance (Ehrlich & Becker, 1972). In flood risk management, the former might include moving valuables out of a flood prone area of the house, and the latter could include landscaping a yard to reduce risk of overland flow. If upfront costs are low enough, self-protection and self-insurance may satisfactorily mitigate risks, particularly if an insurance provider cannot differentiate insurance premiums to account for households that have adopted self-protection and/or self-insurance measures. On the other hand, insurance can work as a disincentive to take measures of self-protection and self-insurance through the well known moral hazard problem.

In many settings where market insurance has been available (and even subsidized), uptake is typically lower than what might be expected based on traditional economic models. One explanation for this is that people tend to underestimate the probability of floods and other natural hazards, and then reason that insurance costs are too high (Browne, Knoller, & Richter, 2015; Kunreuther, 1984). There is also evidence that home buyers do not have access to sufficient information about risks at the time of home purchase (Chivers & Flores, 2002). Other explanations are found in risk perception literature, as well as evidence that government aid following a flood event may create an expectation of post flood recovery assistance that disincentivizes the purchase of insurance (Kousky, Michel-Kerjan, & Raschky, 2018; Raschky & Weck-Hannemann, 2007).

Specific socio-economic factors may be associated with flood insurance uptake. While it is unclear if these factors have a direct influence on insurance uptake, or are merely associated with a more direct causal mechanism, understanding how geographic variations in factors like income, age, ethnic status and housing tenure are associated with flood insurance is important for flood risk management. This information can help predict the variation in flood insurance uptake in response to new policy instruments—such as the construction of flood prevention infrastructure or the introduction of new insurance options or subsidies. Furthermore, understanding the role of socio-economic factors on insurance uptake may reveal underlying vulnerabilities to flood risk, and help plan geographical risk mitigation strategies targeted to vulnerable groups.

### 1.3. Social factors that influence flood insurance uptake

Most current research is based on stated preference through willingness to pay/willingness to buy insurance and other risk mitigation strategies, but there is some revealed preference literature on insurance uptake levels, as well as some research that uses insurance purchase data directly. We consider all in the review below. We stratify the following review by distinguishing household-level and individual-level characteristics.

#### 1.3.1. Household-level characteristics

Household level characteristics have been examined in flood literature for their effect on willingness-to-pay for flood insurance and/or flood mitigation measures. When compared to non-homeowners, homeowners have more incentive to buy protection against flood loss; however, results are mixed, showing both positive (Clark, Griffin, & Novoty, 2005; Hung, 2009; Shao et al., 2017; Zhai & Ikeda, 2006) and negative associations (Atreya, Ferreira, & Michel-Kerjan, 2015; Jones, Clark, & Malesios, 2015; Kousky, 2010). The home is one of the most important assets in an individual's financial portfolio, and risk-averse homeowners may be more incentivized to protect their wealth through flood insurance purchases (Kousky, 2010) while renters may be less likely (Atreya et al., 2015; Shao et al., 2017). In addition, the number of members living in a households has been shown to have a negative effect on flood insurance purchases, possibly as a proxy for income (Clark et al., 2005; Petrolia, Landry, & Coble, 2013; Ren & Wang, 2016; Zhai & Ikeda, 2006). Other research has found a positive association between the number of persons in a household and willingness-to-pay for insurance (Lo, 2013a; Raschky, Schwarze, Schwindt, & Zahn, 2013).

Most research suggests that households with mortgages are more likely to purchase flood insurance (Kousky, 2010; Kriesel & Landry, 2004; Petrolia et al., 2013), however some evidence shows a negative relationship between mortgage and the flood insurance policies-in-force (Browne & Hoyt, 2000). In areas of the United States where federally backed mortgages require flood insurance purchase, this likely increases insurance uptake (Kriesel & Landry, 2004). Rural areas are more likely to purchase flood insurance (Botzen & van den Bergh, 2012; Botzen, Aerts, & van den Bergh, 2009) possibly due to a difference in attitude about risk mitigation in sparsely populated areas compared to urban areas (Botzen et al., 2009).

Years of residence in a home has been shown to have both a positive effect on voluntary flood insurance purchase outside of 100-year flood-zone (Brody, Highfield, Wilson, Lindell, & Blessing, 2017), as well as a weak negative effect on willingness-to-pay to reduce the inconvenience of flood (Zhai & Ikeda, 2006). The longer one has lived in a home the more information they are likely to have received from peers, news outlets and local officials on flood risk while also observing nearby adverse impacts from flooding over time (Brody et al., 2017). Additionally, more time lived in a home may reduce the amount people are willing-to-pay to be accommodated elsewhere in order to reduce inconvenience when a flood event actually occurs (Zhai & Ikeda, 2006).

Household and property value have been shown to have both a positive (Brody et al., 2017) and negative (Lo., 2013a) association with willingness-to-pay for flood insurance. Higher housing values represent a more valuable asset to protect from potential peril, while also serving as a proxy for income, however it may also be associated with self-insurance and self-protection since covering losses is easier for wealthy people who can afford to purchase more expensive homes (Lo., 2013a).

#### 1.3.2. Individual characteristics

The most commonly studied driver of insurance uptake found in the literature is income, with a consistently positive effect on willingness-to-pay for flood mitigation and/or insurance (Atreya et al., 2015; Botzen & van den Bergh, 2012; Botzen et al., 2009; Botzen, Aerts, & van den Bergh, 2013; Browne & Hoyt, 2000; Clark et al., 2002; Clark et al., 2005; Hung, 2009; Jones et al., 2015; Kriesel & Landry, 2004; Lo, 2013b; Lo., 2013a; Oulahen, 2015; Owusu, Wright, & Arthur, 2015; Petrolia et al., 2013; Raschky et al., 2013; Ren & Wang, 2016; Shao et al., 2017; Thunberg & Shabman, 1991; Zhai, Sato, Fukuzono, Ikeda, & Yoshida, 2006). According to the original theory of hierarchy of human needs (Maslow, 1943) flood insurance may be secondary to food, shelter, and other economic necessities. This may explain why low-income households prioritize critical items for survival and are less able to invest in flood protection regardless of perceived danger (Lo., 2013a; Shao et al., 2017). Flood insurance resembles a normal good, where both decisions to purchase insurance (Atreya et al., 2015; Browne & Hoyt, 2000; Hung, 2009; Kriesel & Landry, 2004; Lo., 2013a, 2013b; Oulahen, 2015; Petrolia et al., 2013; Ren & Wang, 2016; Shao et al., 2017), as well as the amount of insurance purchased (Botzen & van den Bergh, 2012; Oulahen, 2015; Owusu et al., 2015) are positively associated with income, suggesting more insurance is desirable to maximize total utility from risk-reduction (Shao et al., 2017). The authors are aware of only one study that found a negative relationship between income and insurance policies-in-force (Kousky, 2010), however the study showed that high-income earners who did insure purchased more coverage.

Age has been shown to have both a positive (Atreya et al., 2015; Hung, 2009; Jones et al., 2015; Kousky, 2010; Owusu et al., 2015; Ren & Wang, 2016; Shao et al., 2017) and negative (Botzen & van den Bergh, 2012; Botzen et al., 2009; Clark et al., 2005; Oulahen, 2015; Väisänen, Lehtoranta, Parjanne, Rytkönen, & Aaltonen, 2016; Zhai & Ikeda, 2006) association with flood insurance purchases and other forms of private mitigation. Age has been shown to decrease willingness to take risks in general (Dohmen et al., 2011), and more specifically, older individuals may be more risk-averse than their younger counterparts with regards to protecting wealth and assets from flooding (Atreya et al., 2015; Edwards, 2010).

Gender has been examined for differences in risk attitudes, with most flood insurance studies showing that males are more likely to purchase flood mitigation and insurance than females (Botzen & van den Bergh, 2012; Botzen et al., 2009; Clark et al., 2005; Petrolia et al., 2013; Ren & Wang, 2016; Shao et al., 2017; Väisänen et al., 2016). However some studies have also shown that women are more likely to buy insurance (Hung, 2009; Raschky et al., 2013), and are more likely to pay to reduce the inconvenience of flooding (Zhai & Ikeda, 2006). Lower uptakes of flood insurance and protective measures for females contradicts much of the literature on gender differences in risk preference, which has typically shown women to be more risk-averse than men (Croson & Gneezy, 2009). One explanation for differences in risk-taking is due to differences in emotional reactions to risky situations, notably that women report more intense nervousness and fear than men in anticipation of negative outcomes, as well as men being more overconfident in their success in uncertain situations (Croson & Gneezy, 2009). The difference observed in most flood insurance literature may suggest that men perceive flood insurance as more valuable than women (Ren & Wang, 2016).

Some studies have shown that education has a positive effect on investment in flood mitigation and flood insurance (Atreya et al., 2015; Botzen et al., 2009; Hung, 2009; Ren & Wang, 2016; Shao et al., 2017), however some studies found the opposite effect (Botzen & van den Bergh, 2012; Jones et al., 2015). Individuals with higher levels of education may be more aware of flood risks, which lead to higher voluntary flood insurance uptake (Hung, 2009; Shao et al., 2017). Employment has been shown to have a positive association with willingness-to-pay for property level flood protection (Owusu et al., 2015), and more specifically, people working as forest or agricultural entrepreneurs are more likely to buy flood insurance (Väisänen et al., 2016), however the reason for this is unclear.

Race and ethnicity have been examined in flood insurance literature, particularly in the American setting. Findings suggest that white individuals are less likely to invest in flood insurance and flood mitigation (Shao et al., 2017), while African American and Hispanic individuals are more likely to purchase insurance, while controlling for all other factors that influence insurance uptake (Atreya et al., 2015; Petrolia et al., 2013). White individuals are less likely to perceive environmental risks compared to racial minorities, therefore increased levels of concern for environmental disasters amongst racial minorities may lead to higher levels of insurance in these communities (Shao et al., 2017).

### 1.4. Predicting the geography of flood insurance uptake

Based on the existing literature, household and various demographic and socioeconomic characteristics seem to have an important association with insurance uptake independent of features of the physical risk landscape. Given that these same factors often vary geographically, it is plausible that geographic variation in insurance uptake can be predicted (at least to some degree) with a model that incorporates these data into predictions. In this research we aim to understand the small-scale geographic variation in flood insurance uptake with an emphasis on understanding some key social indicators of vulnerability and how these both relate to the physical hazards of flooding. Our findings provide a useful starting point for understanding the role of the private flood insurance market on the future impacts of flooding in the study area.

## 2. Methods

Ideally, we would use real information on household flood insurance uptake—provided by either insurers, or through surveys of the population—to assess the pattern of insurance uptake in the study area. However, there are a number of challenges with this approach. First, since insurance only became available recently, current data may not reflect the medium or long term coverage levels. Second, insurance uptake is partly a function of premium price, however price information is proprietary, and private insurers are reluctant to share it. Without controlling for price, any information about uptake is difficult to interpret, since price is associated with both risk level and the willingness to purchase insurance. Finally, survey data of a resolution useful for understanding geographic variation in the study area would be expensive to collect, and could be confounded by a response bias if persons who are more likely to respond are those who have experienced flood events in the past.

For these reasons, we take a meta-analysis approach to our analysis. Meta-analyses and systematic reviews are often used in health research to combine previous research in order to understand the risk factors, effectiveness of interventions, and to predict other outcomes in health research (Glasziou, Irwig, Bain, & Colditz, 2001). Here, we use this approach to generate predictions of insurance uptake by combining predictive models from existing literature with data from the study area, the City of Calgary. This requires us to 1) find and select appropriate literature for inclusion, 2) come up with appropriate predictive models based on model parameters estimated in articles selected for inclusion and 3) pool these predictions into overall predictions of insurance uptake in the study area.

### 2.1. Selection of literature

We used Web of Science to search for all articles published since 1990 on the topic of willingness to buy flood insurance. We used the search string (flood* AND insurance) OR (flood* AND “willingness to buy”) OR (flood* AND “willingness to pay”). We restricted our analysis to articles published in English, and to papers in which researchers modelled factors that influence insurance purchases as either 1) the probability that a household had purchased or expressed an interest in purchasing flood insurance (household-level) or 2) the proportion of the households in an area that had purchased or expressed an interest in purchasing flood insurance (ecological-level). Research was also

**Table 1**
Predictors of flood insurance uptake in studies extracted in meta-analysis.

| | Atreya et al. (Atreya et al., 2015) | Browne et al. (Browne & Hoyt, 2000) | Kriesel et al. (Kriesel & Landry, 2004) |
|---|---|---|---|
| Constant | −7.172 | 0.807 | 0.111 |
| Income | 0.390* | 1.4* | 0.0048 |
| Data from the 2010 Canadian National Household survey on income. We use average household income for Atreya et al., average household income per 1000 for Kriesel et al. and disposable income (as income*0.33) per 1000 for Browne et al. | | | |
| Price | −0.156* | −0.109* | −0.591 |
| Price per $1000 insured for Atreya et al., and Brown et al. and price per $100 insurance for Kriesel et al. | | | |
| Time since last flooding event | 0.023* | | −0.010 |
| For Atreya et al., set to a value of 1 (indicating three years since last flooding event based on their model specification); for Kriesel et al., it is set to a value of 3 | | | |
| Disaster relief spending in previous year (*per capita*) | | 0.017 | |
| Set to a value of $10.54 based on estimates of annual average of *per capita* disaster relief payments in the region from Canadian Disaster Database maintained by Public Safety Canada (Public Safety Canada, 2017) | | | |
| *Disaster relief expenditures per capita* | | 0.009 | |
| *Mitigation assistance* | *0.018** | | |
| *Mitigation expenditures per capita* | | *−0.007* | |
| *Artificial protection* | | | *0.491* |
| Flood risk area | 1.009 | | |
| Based on whether or not house was in a flood zone with 1 in 100 (or larger) return period | | | |
| Distance from water | | | −0.0023 |
| Euclidean distance to closest surface water | | | |
| *Not an NFIP community* | *−0.0327* | | |
| *Mortgage* | | −0.056 | *4.359* |
| *% African American* | *0.0105* | | |
| *% White* | *−0.0002* | | |
| High school education | 0.0435 | | |
| College/university | 0.044 | | |
| Data from the 2010 Canadian National Household survey. | | | |
| Own | −0.0005 | | |
| Rent | 0.001 | | |
| Data from the 2010 Canadian National Household survey. | | | |
| Age 25 - 44 | 0.0043 | | |
| Age 45 - 64 | 0.0472 | | |
| Age 65 + | 0.0565 | | |
| Data from the 2010 Canadian National Household survey. | | | |
| Geographic constant | *−0.741* | | |

The geographic constant accounts for geographic dummy variables specified in the source study. We chose a constant that is the average of the coefficients.

restricted to studies done in Canada and the United States. We further restricted our analysis to studies which provided a table of terms sufficient for reconstructing model predictions (tables of all coefficients, including constants) and descriptive statistics (mean, standard deviation, minimum and maximum) for all model terms. Finally, research was restricted to studies that included a measure of insurance premium price in the prediction of model uptake.

Our original search (without applying restrictions) resulted in 991 articles. Abstracts were then scanned, and after applying all restrictions except price, we were left with 27 articles. Each of these articles was read to identify those that included price in the prediction of insurance and included sufficient detail for reconstructing the reported models—specifically, descriptive statistics of mean, standard deviation, minimum and maximum values. In the final stage, four papers met all inclusion and exclusion criteria. All studies are based on research in the United States. Two studies were ecological level (Atreya et al., 2015; Browne & Hoyt, 2000) and two were household level (Dixon, Clancy, Seabury, & Overton, 2006; Kriesel & Landry, 2004). Atreya and et al. (Atreya et al., 2015) and Browne & Hoyt (Browne & Hoyt, 2000) based price data on aggregate premium price information, and Kriesel & Landry (Kriesel & Landry, 2004) used a survey of premium data for households with insurance, and a modelled price for households without insurance. The fourth paper (Dixon et al., 2006) had only model derived price and was therefore excluded from our analysis. This left three source studies for use in our meta-analysis.

### 2.2. Selecting and parameterizing models

Table 1 summarizes the variables used in our analysis based on the results of the source studies. We provide a brief description of each variable used for which data were available. Log variables are noted with an asterisk (*). Variables in the source studies that were not available in the study area are noted with italics. On occasions when these missing variables have a measureable impact on insurance levels, excluding them would affect the accuracy and precision of model predictions. We attempt to account for the effect of these missing variables by treating them as random error effects with empirical distributions based on the descriptive statistics found in the original articles (see formal description below).

Socioeconomic model variables (age, education, income) were available from the 2010 National Household Survey (Statistics Canada, 2011) at the level of dissemination areas. Dissemination areas are typically the smallest geographic areas available for obtaining data from the Canadian census; in Calgary, these dissemination areas have a few hundred households. Exposure to previous flood was based on whether or not the area in which the location was experienced evacuation during the 2013 Calgary flood event. Objective risk was based on distance to water calculated using Euclidean distance to dissemination area centroids.

Price is a design variable where we estimate the insurance uptake at different prices. We do this because real price is unknown. Price is based on a simple fair premium calculation. For example, a fair annual premium for \$1000 coverage in a 1 in 100 year flood zone is \$10. Since we do not take into account load factors of insurance premiums (which include administration costs and profit taking of the insurance companies) the price is probably lower than the premium in the real world. For this reason we explore a variety of pricing scenarios, including prices differentiated based on the flood hazard level. The specifics are discussed in the results.

Based on these specifications, and for each source study, we create a model to predict household willingness to buy flood insurance in the study area for each of the included studies. For the two ecological studies the model takes linear form,

$$p \sim b\mathbf{X} + a\mathbf{\Sigma} \tag{1}$$

where $p$ is a vector of proportion of households predicted to purchase insurance in dissemination areas, $b$ is a vector of coefficients for which data are available in the study area, $\mathbf{X}$ is a matrix of independent variables, $a$ is a vector of coefficients for which data are unavailable in the study area and $\mathbf{\Sigma}$ is a matrix of randomly generated variables. Variables in $\mathbf{\Sigma}$ are generated from a truncated normal distribution with a mean, standard deviation, minimum and maximum value based on reported variable values in the source study. This ensures that the random error effects take on a realistic range of values.

For the household-level study, the source study model takes logit form, so we model the linear predictors as

$$\mu \sim b\mathbf{X} + a\mathbf{\Sigma} \tag{2}$$

and use the following

$$r = \frac{e^{\mu}}{1 + e^{\mu}} \tag{3}$$

to obtain a prediction, $r$, of whether or not a dwelling has purchased insurance in the study area. This is converted into a predicted proportion of dwellings in dissemination areas by taking the average $r$ in the dissemination area.

Our intent is to predict the uptake of insurance for households in each dissemination area, however the two ecological models predict log of insurance uptake. Simply exponentiating the logged predictions of the ecological models in (1) results in a downward biased prediction. To properly retransform the predictions we use a smearing factor (Duan, 1983) to obtain unbiased predictions of insurance uptake for the models in which predictions are on the log scale.

### 2.3. Pooling predictions

Using the methods described above, we obtained predictions of insurance uptake as a proportion of dwellings for each dissemination area for each of the three studies used to parameterize our models. Pooling predictions from models can often lead to more accurate predictions than selecting best fitting models in forecasting applications (Bates & Granger, 1969; Winkler & Makridakis, 1983). There are many possible ways to combine these predictions, including equal weights, or weights inversely proportional to model fit. We combined the pooled predictions results by taking weighted averages for each dissemination area. However, since the exact weightings can produce different results, we used three weighting schemes: equal weighting of each study (W1), preferentially weighting the individual level study (W2) and preferentially weighting the ecological-level studies (W3). Preferential weighting involved doubling the weights; for example, in the first scenario, the individual-level had double the weight as the two ecological-level studies.

### 2.4. Hazard classification

We used a flood hazard classification method based on Elshorbagy et al. (2017) to classify the level of flood risk in Calgary (Elshorbagy et al., 2017). This classification is not used in the models above, but for contrasting the level of insurance coverage and socioeconomic measures across flood risk levels. The classes are: severe, high, moderate, low and very low flood hazard. The classes were created based on two parameters—elevation above nearest drainage and distance from nearest drainage. This classification scheme has been validated against previous floods in Canadian cities, including Calgary, and showed that the severe area matched the 1 in 100 year floodplain in Calgary (Elshorbagy et al., 2017). For much of Calgary, all but the very low flood risk area is tightly clustered around the two rivers running through the city, the Bow and the Elbow. For this reason, we also reclassify the hazard into a dichotomous class of within the 1 in 100 year flood area (severe to low risk) and outside the 1 in 100 year flood area (very low risk). We refer to this as the simplified hazard map.

### 2.5. Identification of dwellings

The spatial boundaries of census areas (like dissemination areas) do not reflect an accurate distribution of population residence, and as a result can lead to imprecise estimates of flood affected areas (Maantay & Maroko, 2009). We used the following strategy to obtain a more realistic count of private dwellings within the flood zone areas. We first used municipal land use data to clip the dissemination areas, and removed sections of dissemination areas that were not residential. We then generated a uniform distribution of points in each of the clipped dissemination areas equal to the number of dwellings located within them. Dwelling counts within the hazard classes were then obtained by counting dwellings based on the location of these points. Households (family and non-family) are defined differently than private dwellings in the Canadian Census, however the counts tend to be similar in dissemination areas, and for style purposes we use the terms interchangeably here.

### 2.6. Prediction error

The models used to make the predictions contain several sources of error, chief among them is the unexplained variance in the dependent variables. Both ecological studies reported a coefficient of determination ($R^2$). For these ecological studies we add normally distributed random error, with a mean of 0 and a standard deviation $u$, where

$$u = \sqrt{s(1 - R^2)}. \tag{4}$$

The value of s is determined by the variance of the dependent variable reported in the source study. This random variate is added to each prediction of insurance uptake in formula (1) in both ecological models. The household-level study reported a goodness of fit measure based on the proportion of correctly predicted observations rather than the coefficient of determination. We use this in place of $R^2$ in formula (4), and add this random variate to formula (2). These errors do not affect the predictions estimated by the models, but add a measure of variability about the predictions. This provides an overall sense of the sensitivity of our predictions to model assumptions.

We ran 100000 simulations of our predictive models in order to obtain a distribution of this prediction error (PE) for each model, pooling these results as described above above. We use ± one standard deviation of the distribution of simulated predictions as a measure of PE in the results for reporting the number of dwellings purchasing insurance.

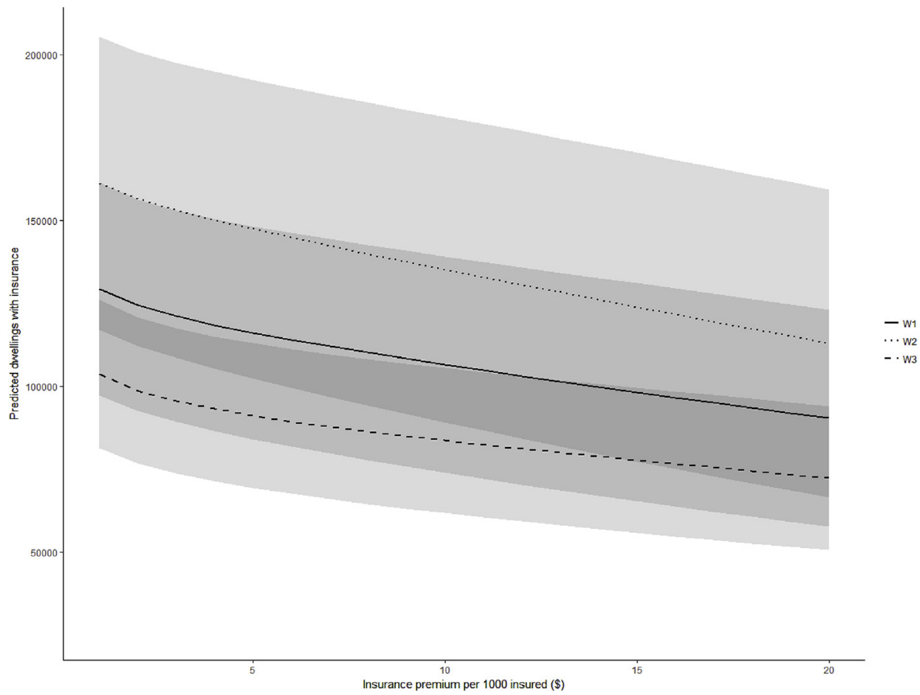


**Fig. 1.** Price and predicted number of households with insurance for three pooling weight methods.

## 3. Results

### *3.1. Overall insurance coverage uptake*

Based on the pooled model we varied the insurance premium to observe the relationship between price (holding other model variables constant) and model predicted insurance uptake for the study area as a whole (Fig. 1). The grey ribbons represent the ± 1 standard deviation in PE across the simulations for each pooling method. The ribbons overlap, but are transparent, so that the darker bands represent areas where the PEs overlap. Values on the y-axis are the predicted number of households in Calgary purchasing insurance. The pattern suggests a negative and almost linear relationship between price and insurance uptake between $1 and $20 per $1000 of annual coverage. Extending the curve out to the right suggests that the pooled estimate is very likely unrealistic at higher prices since the curve converges on '0' demand only at very high prices. Furthermore, extending the curve to the left suggests considerably less than 100% insurance uptake even when premiums have no financial cost.

### *3.2. Geographic variation in insurance uptake*

Fig. 2 is a map of quantiles of model predicted insurance uptake in each dissemination area. Values of 1 are the lowest predicted quantiles of insurance uptake, and values of 5 are the highest predicted quantiles of insurance uptake. The predictions that make up the quantiles are based a constant premium cost of $5 per $1000 insured and the W1 pooling method. Based on this pooled model, this predicts a total of 116071 (PE: 95178, 136963) households with insurance in Calgary. In the real world, premiums set by insurance providers are spatially differentiated based on risk to households, market analysis and other factors. To explore this, we set the premium to $10 per $1000 within the 1 in 100 year hazard area, and a premium of $2 per $1000 outside the 1 in 100 year hazard area. Based on the pooled model based on the W1 pooling, this predicts a total of 120828 (PE: 99075,142697) households with insurance in Calgary, an increase of insurance uptake of about 6% over the constant pricing scheme.

The total estimated insurance against loss based on the constant $5 per $1000 in coverage is $58 million dollars per year, assuming an average of $100000 in damages covered per policy. The total estimated insurance against loss based on the differentiated premium per $1000 in coverage is $42 million dollars per year, assuming an average of $100000 in damages covered per policy.

### *3.3. Hazard levels, insurance and socio-economic vulnerability*

Table 2 shows the number of dwellings, income, dwelling value, percent home ownership and insurance uptake by the 5 hazard classes. The vast majority of dwellings are in areas of the city with low risk levels. Incomes and dwelling values are highest in the highest flood risk hazard class. The lowest income and lowest dwelling value areas are in the moderate and low risk hazard classes. Home ownership is highest in the very low hazard class and lowest in the severe hazard class. The highest percentage of immigrants to Canada is in the very low hazard area, and the lowest percentage is in the moderate hazard area, though the percentages do not vary greatly. The pattern for the percentage of residents that self-identify as a visible minority shows a similar pattern, with the highest percentage in the very low hazard area, however the lowest percentage is in the severe hazard area.

Table 3 shows the variation in predicted insurance uptake (for the constant and differentiated premium levels) stratified by income, dwelling value, home ownership, immigration status and status as a visible minority, as well as by the 5 flood hazard classes. Each variable is sorted in quintiles from lowest quintile to highest quintile. The highest risk regions ('severe flood risk') of Calgary have the highest levels of insurance uptake for the constant and differentiated insurance pricing scheme. However, the very low hazard area has higher insurance uptake and the severe hazard area has a lower insurance under the differentiated pricing model than the constant pricing model. Both income and dwelling value appear to have a roughly linear relationship with insurance uptake. For income and dwelling value, the differentiated pricing scheme results in a higher insurance uptake at the highest quintiles. Home ownership shows a very similar overall pattern to income and dwelling value. There is less variation in insurance uptake across the immigrants to Canada and visible minority variables.

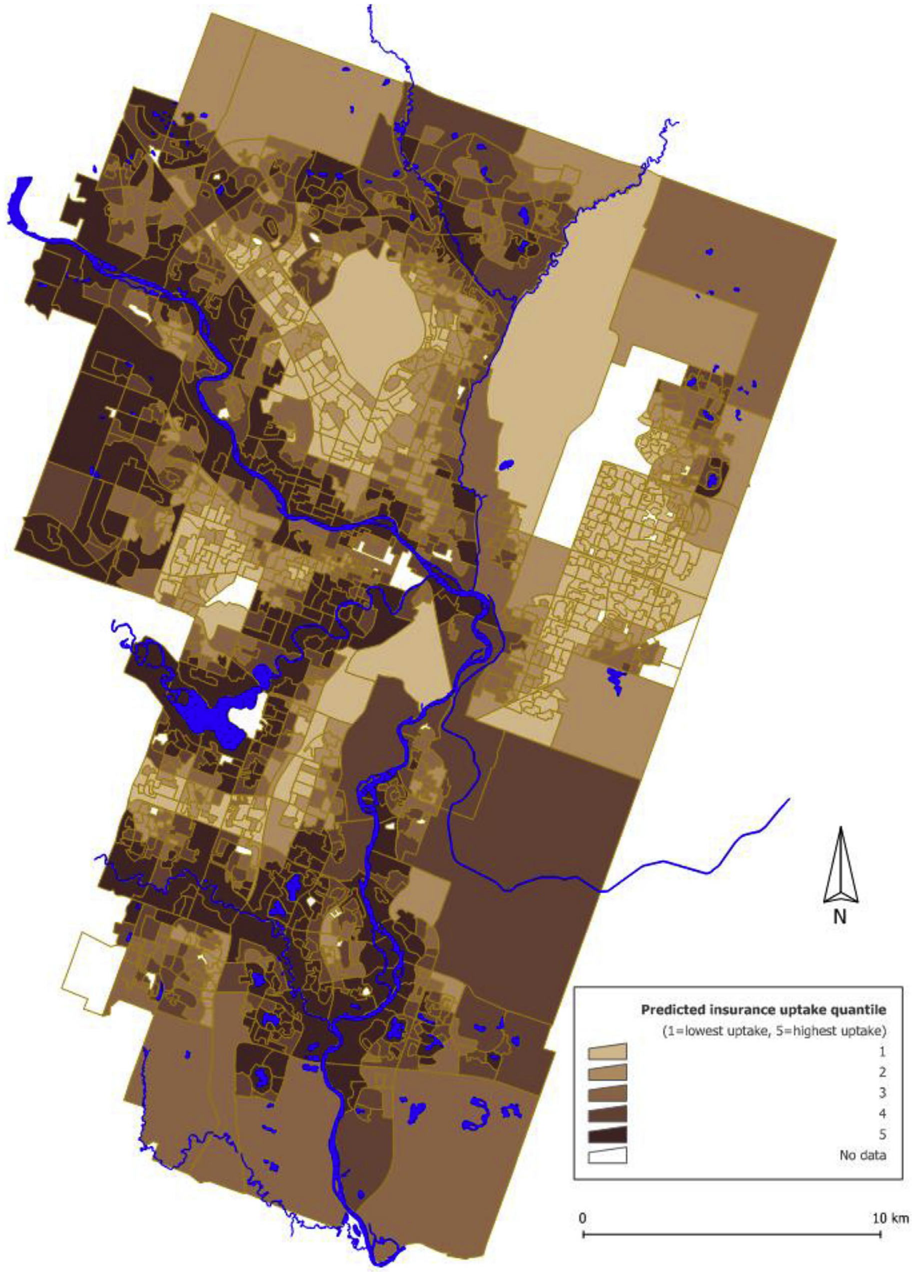


**Fig. 2.** Quantiles of predicted household insurance uptake in Calgary based on the W1 pooled model at a uniform price of $5 per $1000 coverage.

## 4. Discussion

Average predicted flood insurance uptake in Calgary is relatively high for all three pooling methods, though we note the large potential variability around these estimates. Our predictions of absolute levels of insurance uptake are probably of less value than the relative levels, since the study sites in the source literature used to calibrate our models differ considerably from Calgary. Among other things, Canada currently has no equivalent to the NFIP, and the source studies cover larger and more heterogeneous regions. For this reason, the bulk of our discussion below is based on relative comparisons—by geography and by socio-economic indicators—of both flood hazard and predicted flood

**Table 2**
Hazard level and socio-economic measures.

| Hazard level | Number of dwellings | Average Household Income ($1000s)[a] | Average dwelling value ($1000s)[a] | Homeowners (%) | Immigrants to Canada (%) | Visible minority (%) |
|---|---|---|---|---|---|---|
| Severe | 13,786 | 143.83 | 564.79 | 54.59 | 27.25 | 20.34 |
| High | 14,829 | 104.89 | 424.67 | 61.27 | 24.14 | 23.89 |
| Moderate | 12,726 | 88.20 | 417.93 | 57.74 | 22.76 | 26.87 |
| Low | 9192 | 99.73 | 394.00 | 68.94 | 22.92 | 24.78 |
| Very low | 279,185 | 115.99 | 451.89 | 79.06 | 28.06 | 30.91 |

[a] Population weighted averages.

**Table 3**
Predicted percentage of insurance uptake (W1) based on socio-economic quintiles and hazard level.

| | Hazard level (Severe to very low) | Average Household Income, Lowest to Highest Quintiles | Average dwelling value, Lowest to Highest Quintiles | Dwelling owner, Lowest to Highest Quintiles | Immigrants to Canada, Lowest to Highest Quintiles | Visible minority, Lowest to Highest Quintiles |
|---|---|---|---|---|---|---|
| Percentage of households buying insurance at constant price ($5 per $1000 coverage) | 39.42 | 20.36 | 20.61 | 23.02 | 33.76 | 32.34 |
| | 31.95 | 21.97 | 24.03 | 24.02 | 29.74 | 28.78 |
| | 28.86 | 26.18 | 27.93 | 26.20 | 27.12 | 28.21 |
| | 31.34 | 30.32 | 28.27 | 30.88 | 26.54 | 25.94 |
| | 26.70 | 41.51 | 38.14 | 36.45 | 23.42 | 24.86 |
| Percentage of households buying insurance at differentiated price ($2 for very low and $10 otherwise per $1000 coverage) | 36.78 | 20.69 | 21.11 | 23.06 | 35.13 | 33.41 |
| | 29.47 | 22.88 | 25.07 | 24.97 | 30.88 | 30.13 |
| | 26.50 | 27.32 | 29.01 | 27.62 | 28.18 | 29.35 |
| | 29.01 | 31.60 | 29.65 | 32.42 | 27.61 | 26.99 |
| | 28.62 | 43.66 | 39.85 | 38.43 | 24.56 | 25.96 |

insurance uptake.

### 4.1. Flood hazard and socioeconomic indicators

In this setting, higher income is associated with highest flood risk. This is in contrast with some other settings, particularly in the developing world, where flood risk is associated with poverty (Brouwer, Akter, Brander, & Haque, 2007). However, the moderate hazard class has the lowest average household income, and the very low hazard class sits roughly in between these two. This apparently non-linear association between income and flood hazard may be explained by the location of some low income high hazard communities particular to this setting, such as income assisted senior's housing east of the downtown area, but also that some lower income neighbourhoods are close to, though not immediately adjacent to, the river.

Similar to income, higher dwelling value is generally associated with higher flood hazard. House price is responsive to environmental concerns in general (Boyle & Kiel, 2001) as well as flood risks in particular, especially after a flood event (Bin & Polasky, 2004). Our analysis uses census data from prior to the 2013 flood in Calgary, and therefore, may not reflect any short term change to dwelling value indicators immediately following the flood. Nevertheless, the aesthetic value of living near water may increase the value of some property, or offset some of the perceived costs associated with increase flood risk (Geoghegan, Wainger, & Bockstael, 1997; Li & Brown, 1980). The possibly countervailing influences of aesthetic value of living near water and the increased risk of harm make understanding the relationship between proximity to water and price difficult to interpret (Daniel, Florax, & Rietveld, 2009); however, some recent evidence suggests that flood risk may have a larger impact on lower value homes than higher value homes (Zhang, 2016). This would be consistent with the apparent situation in Calgary, and could explain why higher dwelling values in the highest flood risk areas might be more resistant to downward price pressures.

The highest hazard areas are associated with higher proportions of renters than other regions of Calgary. As noted above, some research has shown that home ownership is associated with higher insurance uptake, however this is very contextually specific given the considerable differences in homeownership rates between countries and even between regions. The authors are aware of no research that specifically measures the role of flood risk on rental market development or rental prices, though it's possible that downtown rentals attract a larger proportion of younger persons.

A plurality of immigrants to Canada and persons who identify as visible minorities live in the very low risk hazard area. Previous research has suggested that visible and ethnic minorities are more vulnerable to a variety of natural disaster hazards. This is not simply due to a difference in exposure, but rather, an underlying vulnerability due to poor housing, isolation and cultural insensitivities (Fothergill, Maestas, & Darlington, 1999). While a smaller proportion of residents in the severe hazard area identify as visible minorities than in the lower hazard areas, those who do live in the higher hazard areas may be particularly vulnerable if they face the barriers to risk mitigation found in other research.

### 4.2. Impact of insurance on socioeconomic vulnerability to flood hazard

In Calgary, the severe hazard areas of the city are predicted to have the highest insurance uptake rate, however, since there are relatively few dwellings in these areas (less than 14000), this could still suggest an adverse selection problem—where insurance premiums are extremely high, which leads fewer households to purchase insurance, and results in yet higher premiums. In addition, the affordability of insurance may be a concern in dissemination areas where income is lower and flood hazard is moderate. In these areas insurance uptake is lower due to the interaction of higher premiums and the lack of financial resources, and is very likely to contribute to adverse selection even if premiums are slightly lower than in the severe risk area.

Our results also suggest that the total revenue generated from the purchase of insurance may not fully cover the expected losses associated with floods in the long term. In our models, the total annually generated revenue based on actuarially fair premiums is 42–58 million dollars depending on whether the premium prices are differentiated or constant, respectively. This is considerably lower than the estimated annual cost due to flood losses for Calgary as a whole, which could be as much as 170 million per year (IBI Group and Golder Associates Ltd, 2017). The spatial concentration of high and severe risk to a relatively small number of dwellings near the Bow and Elbow rivers could also mean that the vast majority of Calgary residents have little incentive to purchase flood insurance at premiums that would help cross-subsidize the cost of premiums in higher risk areas. Our predictions may be insufficiently accurate to merit a clear conclusion on the viability of insurance to fully cover losses, but does suggest that further investigation is warranted.

Previous researchers have suggested that insurance purchases and other forms of risk mitigation are price inelastic (Atreya et al., 2015; Hung, 2009; Kriesel & Landry, 2004). The impact of this inelasticity should be a more homogeneous spatial pattern of insurance uptake, even assuming that price varies based on spatially variable determinants. However, evidence for this observation is based on a relatively small number of studies and in many cases models that assume insurance purchases change linearly with demand. In some settings, actuarially fair premiums based on underlying risk may be considerably more expensive, and demand for insurance may quickly decline at these high prices. In spite of the predictions we made here, we would argue that there is insufficient evidence to draw any general conclusion about the sensitivity of flood insurance to price. The models we used to make the pooled predictions are very likely unrealistic at the high premium range, where demand for insurance would certainly be lower than what the model predicts. This is a critical problem in settings where the geographic variation in flood risk is striking. In Calgary, much of the risk is spatially concentrated, meaning that premiums could be unaffordable in some areas.

Lack of variation across immigrant status and visible minority status is at least partly because they were not explicitly modelled in our predictions. For visible minority status, it was not possible to convert Canadian census information into the categories used in the three studies, and none of the three source studies included a term for immigration status. The measure of immigration may be of particular importance for future research, since it has been less commonly of study focus, and is also particularly important in Canada where there is a large and growing population of immigrants. Research on environment perception suggests that immigrants assess risk and environmental hazards differently compared to non-immigrants (Adeola, 2007; Carter, Silva, & Guzmán, 2013).

Socioeconomic vulnerability to flooding has been studied extensively in research conducted around the globe (Adelekan, 2010; Cutter, Boruff, & Shirley, 2003; Fekete, 2009). We did not measure vulnerability directly, and instead, modelled the level of insurance uptake, and described how uptake may differ geographically, and according to a number of socioeconomic measures. This is important since it focuses on the potential of a particular method of risk mitigation to reduce overall vulnerability to floods. Our analysis suggests that the severe hazard level areas may also have the highest rate of insurance uptake. Uptake is even higher if insurance premiums are lower through cross-subsidization of premiums. Cross-subsidization involves increasing premium prices in low hazard areas to make insurance more affordable in high hazard areas. The two pricing schemes we use serve as a simple example of the impact of cross-subsidization in flood insurance. The constant pricing scheme we employ is an extreme example of this, since price is uniform; under this scheme, insurance uptake is higher in the severe hazard area than it is under the differentiated pricing scheme, where prices more closely reflect real levels of risk. However, the result of this cross-subsidization is that middle and lower income families in very low hazard areas would be paying higher premiums to make insurance more affordable in higher income high hazard areas.

### *4.3. Limitations*

The lack of comprehensive publicly available data on insurance premiums makes insurance uptake hard to assess generally, and our findings, consistent with most research to date, shows a relatively simple relationship between price and flood insurance purchases. In the real world, insurance uptake may increase at a faster rate as price approaches zero, and it very likely declines quickly (though still monotonically) as price increases. We used a fairly restrictive range of prices (between $2 and $20 per $1000 of coverage) in our analysis since this is consistent with other literature, and is also similar to premiums charged in Calgary based on an informal survey of insurers performed by the authors. Nevertheless, our research does not improve understanding of insurance uptake at pricing extremes.

Our search of the literature found only three studies that met the inclusion criteria. We may have missed other studies in our search, and it is possible that these three represent too small a set to offer generalizable findings. Furthermore, none of the studies is from Canada, and may be a poor proxy for how people are likely to make flood insurance purchases in this setting, particularly because U.S. research is focused mostly on coastal rather than river flooding. Nevertheless, our pooled predictions are generally consistent with the results of research from other parts of the world, which has found price and income to have some impact on the uptake of flood insurance (Hung, 2009).

Our predictions of insurance uptake may under or over predict real insurance uptake. First, private insurance uptake is likely to be greatly influenced by the marketing strategies of the insurer. Our predictions do not account for the way that insurance is marketed to residents; for example, it may be that insurers target their product to low hazard areas more than higher hazard areas. Higher uptake in low hazard areas could cross-subsidize premiums in high hazard areas, and in turn, make insurance more affordable and increase uptake. Furthermore, we did not take into account that household self-protection measures may decrease premium costs, and further increase uptake. On the other hand, the inclusion of a mortgage term in our predictions may have resulted in over-prediction. In the United States, the NFIP requires that some mortgage holders buy flood insurance, and this very likely explains the strong effect of mortgages reported in some of the literature. However, an equivalent scheme does not exist in Canada, so the effect of mortgages is likely to be smaller in our study region. This could have lead to over-prediction in our model, which included a mortgage effect.

Finally, and perhaps most importantly, our predictions may be affected by missing variables. The three source studies contain data that were not available in Calgary, and we generated simulated data of these missing variables to scale predictions in our study setting. Missing data that were included in the source studies include information on government policy and ethnicity. If missing data are uncorrelated with other variables in the models (and assuming that the models in the source studies were correct), then our approach would produce unbiased predictions, since the parameter estimates we used would be unaffected by the presence or absence of other variables in a model. However, the variables missing in our analysis may be correlated with other variables in the models. This would impact our predictions if the correlations were strong, and or the variables had a large direct impact on willingness to buy insurance. While this is an important shortcoming, we note that our predictions do incorporate data that is most consistently reported as important in the literature—namely income, price and objective risk level. As such, it is plausible that the bias is relatively small, particularly if we assume that the source studies were judicious in their choice of variables—excluding terms that were highly correlated with each other.

## 5. Conclusion

In spite of these limitations, we think the predictions provided here offer some useful information about flood risk, socio-economic measures and insurance uptake in Calgary. Our analysis includes commonly studied predictors of insurance uptake found in the extant literature—specifically, income, price and objective risk levels. Income in particular is a very commonly studied and consistently positive predictor of insurance purchases. We found that highest flood hazard areas tend to have higher incomes and higher dwelling values than lower hazard areas. We also observed that insurance uptake is highest in the high income and high hazard areas, though perhaps not high enough to address the expected costs of flooding in Calgary over the long term. Future research must obtain clearer information about insurance uptake based on price, ideally using revealed preference data or other data collection methods that will measure insurance purchase behaviour realistically.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2018.05.007.

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