MAPPING AND MODELLING THE PROBABILITY OF TREE-RELATED POWER OUTAGES USING TOPOGRAPHIC, CLIMATE, AND STAND DATA

by

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Abstract

Trees routinely fall across electrical power lines during severe weather events interrupting the power distribution to residential and business customers. Electricity utilities are responsible for generating and distributing power to customers, and managing tree-related hazards adjacent to transmission and distribution lines. To clarify the circumstances under which tree-related outages occur, the relationship between outage frequency and various climate, topographic and stand attributes were investigated. These variables were then used to fit outage probability models using logistic regression. The first study modeled the probability of tree-related outages in the transmission grid across the province of British Columbia (BC) using climate and topographic data. The second study modeled the probability of tree-related outages in the distribution grid for the North Shore region of the BC Lower Mainland using climate, topographic, and stand data. Models for the province fitted the data quite well (c-values ranging from 0.74 to 0.77). The North Shore had the highest density of outages per length of circuit within the province. These local models fit the data less well than in the provincial study (c-values ranging from 0.62 to 0.63). Key variables selected by the models were MC2 average hourly precipitation, MC2 average hourly wind speed, MC2 top 5 events wind speed, BC Hydro annual average wind speed, elevation, ground slope, topographic exposure, crown closure, stand height, and stand age. Vegetation management plans should continue to reduce the risk of outages by eliminating hazard and danger trees from stands adjacent to power lines. The outage density and probability maps could be useful tools for locating circuits that are more susceptible to outages and in customizing local management and ROW design regimes.

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1.0 Introduction

1.1 Background

Power outages occur when the electricity supply to customers is interrupted. Outages can be caused by fallen trees, vehicles accidently hitting poles, and wildlife affecting the lines or supporting structures, among other things (BC Hydro Corporation 2007). Rights-of-Ways (ROWs) are corridors through the landscape within which the power lines run. ROWs are kept open to create a clearance zone between the lines and the surroundings (e.g. vegetation and buildings). ROW vegetation management programs reduce tree-related power outages (Holewinski, Orr & Gillon 1983, Lee and Wolowicz 2007). However, trees are known to cause a significant proportion of power outages in both the transmission and distribution systems (Rocray 1983, Simpson and Bossuyt 1996, Appelt and Goodfellow 2004).

Tree related outages are mostly caused by trees that fall across the lines during severe weather events. The wind or snow loading on the crown overcomes the stem-root strength or the root anchorage causing the tree trunk to snap or the whole tree to be uprooted (Mitchell 2000a). Other causes of tree-related outages include fallen branches or branches growing into contact with the lines (Guggenmoos 2001). In BC, the electricity grid extends across the province through forested areas in a variety of terrains and climates. In the fiscal years of 2001 to 2005, BC Hydro has been spending $2 million/year over the amount budgeted for repair of tree-related outages ($4.3 million/year) (BC Hydro Corporation 2007). To place this in context, BC Hydro spent $9 million in 2007 for Information Technology, Human Resources, safety, and management services for overhead circuits (BC Hydro Corporation 2007). These figures indicate that there are

significant potential savings if the factors that contribute to outages are better understood and preventative actions can be taken.

Between August 2003 and July 2010 the Crown Corporation, BC Hydro, was split into two entities to promote the development of regional transmission organizations in BC (BC Hydro Corporation 2010a). The BC Transmission Corporation (BCTC) was responsible for transmitting high voltage electricity over long distances, connecting the generating stations which were owned by the British Columbia Hydro Corporation (BC Hydro) to terminals and substations also owned by BC Hydro. BCTC was also responsible for the operations, maintenance, and planning of BC Hydro high-voltage electric transmission system (BCTC - Vegetation Management Department 2008). This changed with the Clean Energy Act 2010 (Legislative Assembly and the Queen's Printer) which reunified BCTC and BC Hydro under the BC Hydro name. This thesis research was performed before the two companies were reunified. Therefore, they will be treated as two different companies for the remainder of this document.

1.2 Thesis objective and questions

The main objective of the thesis was to develop statistical models that would identify factors that contribute to tree-caused outages and predict outage locations caused by trees during wind events. Along with outage data, topographic, climatic, and stand data was used in this analysis.

My research questions were:

1) are tree-related outages localized in clustered patterns, or are they spread randomly throughout the study area;
2) what do locations with higher concentrations of outages have in common in terms of topographic, climatic, and stand conditions;

3) can topographic, climatic, and stand variables be combined to predict the locations of tree-related outages?

A secondary objective of my research program was to produce maps of outage probability and to make recommendations for improved assessment, monitoring, and management of ROWs to reduce the potential for tree-caused outages.

1.3 Approach

I used two outage datasets in this study. The first was supplied by BCTC covering the transmission grid (provincial scale). The second dataset was provided by BC Hydro covering the for the distribution grid across the municipalities of North and West Vancouver (BC Hydro's North Shore Region). The potential explanatory datasets include spatially gridded topographic variables derived from Terrain Resource Information Management (TRIM), climate variables derived from numerical weather prediction modelling, and vegetation resource inventory data. I begin by reviewing the state of knowledge on the prediction and mitigation of tree-related power outages (Chapter 2). In Chapter 3, I examine seasonal and spatial patterns in the BCTC provincial outage dataset, examine trends in outages for individual topographic and climatic variables, fit logistic regression models, and produced maps of the selected models. This process is repeated with the BC Hydro regional outage dataset in Chapter 4. I conclude the thesis with an integrating discussion and a series of recommendations.

2.0 Literature review: predicting and mitigating tree-related power outages

2.1 Electricity journey

Hydroelectricity is the main source of electricity in Canada (59%), particularly in BC (90%) where geographic and hydrographic conditions favour its production (Natural Resources Canada 2009). Generators convert turbine mechanical energy into electrical energy and transformers located within switching stations convert the generator low-voltage electricity into a higher voltage. This electricity is transmitted at voltages of 230 to 500 kV in alternating current over long distances and at 69 kV to 138 kV for shorter distances. Direct current transmission may be used to cross bodies of water or in specific cases where there is a need to have full control over the amount of power flowing over the line such as the circuits feeding Vancouver Island (BC Hydro Executive Operations 2002). Transmission lines terminate at substations, which contain transformers that reduce the voltage of the electricity to less than 69 kV. The electricity is then distributed to BC Hydro customers via approximately 55,000 km of distribution lines (BC Hydro 2009). Transmission lines usually run over great distances through wider right-of-ways and at greater heights above the ground than distribution lines. In consequence, the transmission grid has fewer tree-related outages than the distribution grid. On the other hand, transmission outages tend to leave more customers without power because of the cascade effect.

2.2 Circuit components, line arrangements, and other structures

The electrical grid refers to the entire network of generating stations, terminals, substations, conductors, poles and steel towers (Young & Company 2001, BC Hydro 2009). Across North America, this grid is highly integrated. This enables electricity to flow to areas of high demand from areas with surplus production. However, this linkage also introduces vulnerabilities since

failure in one portion of the grid during periods of peak demand can lead to overloading and a cascade of failures in other portions. A good example is the August 14th, 2003 blackout that affected the Northeast of US and Canada, resulting in an estimation of 50 million people without power for up to 4 days (U.S. and Canada Power System Outage Task Force 2004). Conductors (or phase) are the physical structure that transmits the electricity. Overhead conductors are usually uninsulated (which means that they are exposed to external contact) and supported by poles. There are typically three conductors within each circuit (combination of conductors transporting electricity). Feeders are a class of conductors used in the distribution grid to provide electricity to the customer. These are typically insulated, located in urban or modern suburban settings and are often buried. Transmission poles or towers are typically made of steel or concrete. Distribution poles are made of wood, concrete or steel. Underground systems are not exposed to tree-related outages, but are at risk from damage during subsequent construction or soil movement. Goodfellow (1995) compared the expense of installing underground versus overhead systems. Underground systems are more expensive than overhead because of the material used (e.g. conduit pipes and vaults) and due to the labour required for pulling cable into the ducts during the installation process. Underground cabling can cost from 200 to 400+ times more than a 3-phase overhead system.

2.3 Power outages

Electrical utilities aim to generate and deliver electricity or electrical services to residential, business and industrial customers in a safe and reliable manner (Goodfellow 1995, Guggenmoos 2003). A power outage is full or partial loss of electricity supply to one or more customers (BC Hydro Corporation 2008). Power outages can be planned or unplanned. Planned outages occur when maintenance or upgrades are necessary (e.g. line extension, maintenance of infrastructure etc). Planned outages can also be requested by customers when required for maintenance or

installation of equipment and construction. Unplanned outages are non-planned disruptions in the electrical supply. BC Hydro further subdivides planned and unplanned outages in its annual distribution service reports (Table 2.1).

Table 2.1. Type of outages differentiated by cause.

Type of Outages	Definition
Outage	Full or partial loss of service to one or more customer. Generally outages <= 1 minute are considered momentary and are not included in the general statistics
Customer Requested Outage	An outage requested by a customer that interrupts other customers as well
Distribution Outage	All outages on the distribution system including *Hydro planned* and customer requested outages but excluding *source outages*
Forced Outage	An outage caused directly by the trouble cause (e.g. fallen tree broke the conductor and power is out before crew arrives onsite)
Planned Outage	An outage that last longer than 1 minute. Usually instigated by BC Hydro, for the purpose of system extension, improvement, maintenance, repair or switching, except those involving street/lease lights and individual services
Repair Outage	An outage taken by line crew to perform repair on a trouble call (e.g. crews opening a cutout to remove branch from a line). It is different than *planned* outage.
Source Outage	An outage caused by *trouble* or *planned* work on the generation, transmission or substation equipment that results in an outage in the distribution system

Source: adapted from BCTC Distribution Service 2007/2008 Performance Report

Unplanned outages occur when two or more phases come into contact with each other, or are bridged by a conducting object (e.g. branch), or when a wire breaks, or when a wire comes into contact with the ground or with a grounded object (e.g. tree). There are numerous causal factors, including very strong winds, snow or debris avalanches knocking the wires and supporting structures over, by snow/ice loads overloading the wires or supporting structures causing sagging

or failure, trees or branches falling on or breaking power lines, vehicles hitting the poles or wires, wildlife such as beavers chewing poles, vandalism, and conductor sag (line sags closer towards the ground due to material expansion resulting from increased heat). In rare situations, flashovers occur when suspended particles in the air cause a discharge of electricity to the ground or between phases. Wildfires can also damage supporting structures. Outages caused by adverse weather include lighting, snow/icing on the wires, and catastrophic winds, among others (BC Hydro Corporation 2008). Trees and adverse weather have been responsible for the majority of outages. In the fiscal year 2007/2008 they accounted for 18 and 21% respectively (BC Hydro Corporation 2008). In this study, the focus is on tree-related outages, and in particular the tree failures associated with severe weather events.

2.4 Hazard management – avoiding tree-related outages – ROWs maintenance

Electricity utilities attempt to minimize tree-related outages through the management of vegetation under and adjacent to overhead lines (Lee and Wolowicz 2007). This typically leads to cleared rights-of-ways (ROWs). Vegetation maintenance is usually performed in cycles according to the nature and growth rates of surrounding vegetation (Radmer et al. 2002). Utilities may own or lease the land through which the ROW travels (BC Hydro 2011), but even when they do, these corridors are typically narrow, and for the lower voltage lines, clearance areas is less than a tree-length on either side of the overhead lines. In urbanized areas there is typically a trade-off between cleared ROW width and amenity value of trees.

Some trees are classified as danger or hazard trees. Danger trees are the ones that are tall enough to hit the lines in case of failure. Hazard trees are individuals with high probability of failure, as result of injury or disease (e.g. damaged trunk, root rot), that are capable of hitting the lines (Poulos and Camp 2010). Eliminating danger and hazard trees is a very expensive process

(Simpson and Bossuyt 1996). The limited budget for maintenance forces vegetation managers to prioritize the location and timing of maintenance activities. The magnitude of the problem can be inferred from BCTC's Tree Edge program which commits a $3 million dollar budget per year for a 10 year period to maintain areas with higher susceptibility to tree-related outages and enhance system reliability (British Columbia Transmission Corporation 2010). Deferring maintenance comes at a cost. According to Browning et al. (1997) a 6 year deferral in vegetation maintenance increased the time required to prune each tree by 4 minutes per tree (17 to 21minutes). Porteck et al. (1995) compared different techniques commonly used in ROW maintenance. They found out that complete saw cut followed by herbicide treatment to the cut surface gives the greatest interval between re-treatment. Ideally, ROWs vicinity should be populated by trees/stands that are adapted to the local wind conditions, reallocating budget to outage maintenance to adverse weather related outages.

2.5 Outage impacts and magnitude

Tree-related outages caused by severe weather events can affect large numbers of customers over extensive areas. According to Guggenmoos et al. (2007) 10 million customers supplied by the western grid (United States) were left without power due to flashover caused by blowing debris during two distinct events in US in 2006.

In urban areas there are more options for restoring power when an electricity outage occurs than in rural areas. Urban areas have more ways of redirecting the power from alternative sources of energy (BC Hydro Corporation 2007) (such as the thermal plants) from the Burrard Generation Station, Prince Rupert Generation Station, and Fort Nelson Generation Station which work on natural gas and are used during transmission outages or from different circuits (BC Hydro Corporation 2010b). In the past rural areas expect to experience long lasting power outages, but nowadays they are more reliably due to improved vegetation management, shielded conductors

(lighting proof circuits), and circuit reconfiguration, which consists in redirecting power from other circuits to supply areas in need (BC Hydro Corporation 2007).

2.6 Transmission management and inspection plan

The Western Electricity Coordinating Council (WECC) is responsible for regulating the transmission electricity performance in utilities from Mexico to Canada (Western Electricity Coordinating Council 2009). Because of the potential for cascade failures across when part of the grid fails, the WECC stipulates that member utilities such as BCTC have to develop, document, and implement a Transmission Management and Inspection Plan (TMIP). The TMIP establishes the maintenance and inspection activities accordingly to the Transmission Management Standards and there is a penalty process for non-compliance (Compliance Process Task Force 2004).

2.7 Vegetation management plans

BCTC has developed the Integrated Vegetation Management Plan (IVMP) for Transmission Rights-of-way which aims to increase the reliability of the transmission grid through improving maintenance techniques as well as access to lines (BCTC - Vegetation Management Department 2008). In addition to improving system reliability, the IVMP addresses public and worker safety and the risk of fire caused by vegetation contact with the circuits.

In the long term, the IVMP aims to promote low-growing plant communities under and adjacent to overhead lines that require less frequent maintenance. Vegetation is managed in cycles based on vegetation growth rates. Normal cycles vary from 4 to 12 years but areas populated with fast-growth vegetation can be scheduled to shorter cycles (e.g. 2 to 3 years). Trees are classified for treatment based on a number of biological and financial factors (e.g. stem height, diameter at breast height, number of stems, growth rate, cost of treatment, financial value of stem, and fuel

loading – fuel produced by the leftover debris). A variety of techniques are used in the vegetation management (e.g. slashing, mowing, girdling, grooming, pruning, and chemical). The IVMP aims to comply with First Nations traditional rights, landowners, public, stake holders, and government and corporation interests as well as to maintain or increase biodiversity (BCTC - Vegetation Management Department 2008).

BC Hydro has developed Pest Management Plan (PMP) for Distribution Line Corridors (BC Hydro and Power Authority 2010). Similar to the BCTC IVMP, this PMP is intended to assure a reliable power supply and public and worker safety in the vicinity of distribution line corridors. Practical and cost effective procedures to maintain satisfactory line clearance are defined by this vegetation management plan. Application of natural (e.g. crushed rock) or artificial material (e.g. asphalt or concrete) is used to avoid vegetation growth. Increase public awareness and multiple uses (e.g. recreation, live stock - (BC Hydro 2011)) for the line corridors are accounted for in this plan. BC Hydro commits to use technologies such as Geographic Information System to aid in plan implementation.

2.8 Right-of-ways

Right-of-ways are created to reduce the potential of contact between the utility structures and the surrounding vegetation. The long term goal of vegetation management for utility companies is to establish a predictable and low growing community of vegetation under and adjacent to the corridors (Cieslewicz and Novembri 2003). These corridors vary according to the voltage the circuit it is carrying and the consequences of service disruption in that circuit. High voltage circuits or transmission circuits (138 kV to 500 kV) typically have wider ROWs because they carry higher voltage electricity and an outage in these circuits would affect a greater number of customers. Higher height lines and more robust structures produce greater line clearance. On the other hand low voltage transmission circuits or distribution circuits (69 kV and less) typically run

within narrow ROWs. In some cases, surrounding trees are taller than the power lines and branches are within a 3 to 5 m horizontal distance from the lines. Outages are negatively correlated (r=-0.91, p=0.0041) with line clearance (Guggenmoos 2007). Guggenmoos (2001) estimates that a horizontal line clearance of 6 to 7 m reduces by 80% the risk of a 20 m tall tree striking a line that is 9 m off the ground. Guggenmoos et al. (2007) recommended ROW widths of 60 to 70 m for transmission lines in forested terrain in the New England and New York region.

2.9 Right-of-way and forest edges: similarities and discrepancies

In forested terrain, ROW edges have similar dynamics to harvested cutblock edges. Climatic and topographic factors affect the wind and snow loading on edge trees. The main difference would be that ROW edges may have been cleared when stands were young and have been exposed for long periods of time, which means edge trees have had time to develop more windfirmness than the suddenly exposed trees along cutblock edges. However, where ROWs are widened, or new ROWs are cut through forested areas, the edges would experience the same abrupt change in wind exposure as freshly exposed cutblock edges, albeit usually for shorter fetch (wind travel) distances than occur within cutblocks.

Luken et al. (1991) compared seedlings and saplings growth in 20 ROWs in northern Kentucky (US). They found that forest edges had higher seedling and sapling basal area than farther inside the forest. This difference likely reflects the increased resources (e.g. water, nutrients and sun light) inside the stand at the edge of the ROW.

Trees cause distribution system interruptions by causing physical damage to overhead utility structure (mechanical failure mode), or by providing a pathway between conductors and/or the ground (Goodfellow 1995, Appelt and Goodfellow 2004). There are three ways that trees cause

these system interruptions: fallen trees, fallen branches, and grow-ins (Guggenmoos 2001). Grow-in occurs when branches grow towards the line and in contact with it result in electricity discharge from the conductor - or phase (structure that carries the electricity) to the ground (phase-to-ground outage). While Rees et al. (1994) found that only 2% of outages in the region of Maryland – Baltimore were caused by this category, Simpson and Bossuyt (1996) studying outage causes in Brockton territory (US) found that grow-in was responsible for 4% of the total outages.

Fallen branches are the second most common tree-related outage cause. Large branches landing on conductors can cause outages either bridging phases (phase-to-phase fault) or breaking the conductor mechanically (Appelt and Goodfellow 2004). Goodfellow et al. and others (1995, 2004) found that the length of the branch and diameter of the branches are important predictors of the likelihood of a power outage. Thin branches are less likely to cause outages when compared to thick branches because they burn before shorting the circuit. Thicker branches, on the contrary, have more biomass, which increases the chance of formation of carbon path, shortening the circuit resulting in outage. Tree species and wood/moisture properties are also important factors in this type of outage (Peterson 2004) .

Luley et al. (2002) studied branch failure due to wind gust speed in leafy and leafless periods in Rochester, New York State. The authors found that in the leafy period (May – September), wind speeds of 50 to 85 mph (80 to 137 km/h) caused an increase in branch failures in 0.5 and 5% of trees, respectively. The authors developed a linear regression model to predict branch failure using the 5-second wind gust speed. The equation had a coefficient of determination (r^2) of 0.64. Little improvement in this regression was achieved by adding hourly precipitation data (r^2=0.66) collected an hour before and during the event.

2.10 Windthrow definition

The third type of tree-caused outage is when mechanically unstable trees fall across the conductors breaking the wires, or causing a conduction pathway to the ground. This can often be caused by windthrown trees. Wind can break or uproot trees depending on root anchorage, bole and branch strength, aerodynamic properties of the tree crown, and the direction and characteristics of the wind within and above stand (Stathers, Rollerson & Mitchell 1994).The wind above the stand depends on location, local topography, climate, aspect, and slope properties of the site. The wind within the canopy depends on the width of any adjacent gaps, the orientation of the stand edge relative to wind direction and canopy density (Moore 1977). Mitchell (2000a) describes the physical process of windthrow, with peak winds acting on the tree crowns producing a turning moment at the base of the tree that exceeds the root soil anchorage and cause the tree to uproot. Windsnap is another type of windthrow and it occurs when the root is well anchored to the ground causing the stem to fail (snap) leaving part of the trunk and stump still in the ground. In this thesis research, the term 'wind damage' was used to describe trees that were uprooted or had their trunk snapped and where branches were broken off during wind storm. Both healthy and unhealthy trees are susceptible to windthrow; however certain stem or root defects make failure more likely.

2.11 Tree hazards

In the context of electrical transmission/distribution circuits, many studies distinguish between hazard trees and danger trees. Hazard trees have defects in their physical structure (decay, poor anchorage, poor form, and narrow angle crotches), suppression by others, leaning, or previously damaged by wind, snow, and ice (BCTC - Vegetation Management Department 2008, Guggenmoos 2003). Danger trees are any tree which, on failure, is capable of interfering with reliable transmission of electricity, or will be tall enough within five years that it could pose

danger to the lines if it falls (BCTC - Vegetation Management Department 2008). Poulos and Camp (2010) identified key attributes that differentiate hazard trees from danger trees. Height-to-diameter ratio, total tree height, and live crown ratio proved to be useful in differentiating hazard trees from danger trees. Ruel and Pin (1993) studied stand and tree conditions along power lines located in Quebec after a blowdown. They found that most of the fallen trees had visual defects. It appears that tree visual inspection plays an important role in electricity distribution liability. The contrary was also found by Simpson and Bossuyt (1996) who found that 56 % of the failed trees in the Brockton area (US) had no visual defects. Van der Kamp (2007) evaluated the consistency of arborists in identifying tree defects when using tree hazard assessment procedures that are used by BCTC arborists. Van der Kamp concluded that although arborists were well trained and followed the same field guide, considerable differences were found between arborists' verdict, regarding risk rating and recommendations. This suggests that a more fundamental analysis should be made when assessing danger trees to see if there are other classes of traits beyond defects and poor form that are associated with higher likelihood of failure.

2.12 Factors contributing to tree failure

Stem slenderness is the ratio between height and diameter (HDR) of a tree. Trees with higher HDR are tall with relatively small diameter and typically have lower mechanical stability (Byrne, Mitchell 2007). Trees become more slender when stand densities are high as a result of competition for sun light (Mitchell 2000). Vulnerability to windthrow also increases with stand height and site quality (Lanquaye-Opoku and Mitchell 2005). Root diseases affect tree stability as the root system is weak and does not provide the appropriate resistance during wind events. Similarly, trees with stem defects are less able to resist bending stresses induced by wind, representing a hazard for tree stability (Shea 1967).

Tree anchorage is a function of root system and soil properties, including soil moisture. Kamimura et al. (2009) found that root plate (roots distribution in the soil horizons forming a network-like root system, often 4 m in diameter and 0.4 m in depth - (Stathers, Rollerson & Mitchell 1994)) width, root plate volume, and water content inside the root plate were positively correlated with tree resistance to overturning. On the other hand, high soil water content below the root plate reduced tree resistance. Soil depth and texture affect tree stability. Ruel (2000) found more windthrow on shallow till soils than on deep till soils. Elie et al. (2005) found that jack pine (*Pinus banksiana* Lamb.) (tap root system) wind resistance decreased drastically on shallow/stony compared to deep/low-stony soils. However there is an interaction with species, since he found no significant difference in wind resistance of black spruce (*Picea mariana* (Mill.) BSP) for the different soil types.

Air mass movements are influenced by the landscape configuration. Ruel et al. (1998) found that sites with greater terrain exposure were more susceptible to windthrow because they are less sheltered from winds coming from any direction. Aspect is also a factor. Mitchell et al. (2001) found sites with different aspects are affected differently. Steep slope sites were more susceptible to be damaged by winds coming towards the slope facing direction (Quine 1994, Ruel, Pin & Cooper 1998). Wind speed generally increases with elevation (Mitchell et al. 2008). As topography plays an important role, ways of measuring the wind in these complex terrains have been developed for simulation and forecasting purposes using numerical weather prediction (NWP).

NWP models such as the Canadian Mesoscale Community Compressibility Model (MC2) and the Pennsylvania State University / National Center for Atmospheric Research numerical model (MM5) (Stull and Nippen 2008, Modzelewski and Bakhshaii 2009) have been used as an input in empirical modelling of clearcut edge windthrow for large geographic areas in BC (Mitchell,

Hailemariam & Kulis 2001, Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell 2005, Mitchell et al. 2008). NWP and physical airflow models have been used elsewhere to evaluate damage patterns caused by historic wind storm events (Ruel et al. 1997, Mitchell et al. 2008). Guthrie et al. (2010) found that NWP modeled rainfall was a useful predictor of landslide occurrence during a single winter storm event on Vancouver Island. They found that 88 % of the landslides occurred in areas with > 80 mm of (simulated) rainfall in a 24 h period. However, not all tree-related outages occur during storm conditions. Xu et al. (2003), in a study in the distribution grid of North and South Carolina, investigated tree faults under various weather conditions (e.g. fair, cold, rain, wind, wind and lightning, lightning, hail, snow, ice, and hot). They found that tree faults occurred more often in fair weather, during lighting storms, and in windy weather.

2.13 Wind events

Wind damage can be catastrophic or endemic. Catastrophic damages result from extreme winds that recur infrequently in a given location. Endemic damages result from routine peak wind events often in the same location. Catastrophic wind events produce severe, localized damage, often with a high proportion of stem snapped trees and are produced by a variety of different weather systems, including tropical cyclones, extra-tropical cyclones, thunderstorms and tornadoes (Everham and Brokaw 1996). Mitchell (2000a) classifies as routine (or endemic) winds the storms that recur every 1-3 years. These peak events affect mostly recently open areas (e.g. recent cutblock edges) and produce a high percentage of uprooting.

2.14 Risk assessment

Risk is the probability of a tree-related outage occurring multiplied by the consequences (e.g. cost of repair, customers affected, etc.) of this outage. The probability of a tree hitting a power line depends upon the factors reviewed in previous sections. The costs of tree-caused outages can be considerable. Costs of power interruptions to customers are difficult to quantify, and are not borne by the electrical utilities, which often have local monopolies. However the utilities do bear the system repair costs, and may be liable for injury or fires caused by fallen lines. During the five years prior 2006, BC Hydro budgeted of $4.3 million/year for storm damage repairs. Repairs in 2006 cost 9 times more than this budgeted amount (Table 2.4).

Table 2.2. Summary of 2006/2007 winter storms impacts and repair costs

	No. of Circuits Affected		Area Affected	No. Of Customer Affected				Cost of restoration
Events	Transmission	Distribution		at peak	24h +	48h +	72h +	(in millions of dollars)
Oct 27/06	9	12	Burns Lake, Smithers, Vanderhoof	19,900	8,231	4,457	2,431	1.9
Nov 15/06	8	100	Lower Mainland and Vancouver Island	226,000	55,000	1,200	200	6.3
Nov 26/06	12	150	Lower Mainland and Vancouver Island	92,600	72,500	25,000	2,703	8.4
Dec 11-15/06	12	181	Lower Mainland and Vancouver Island	240,300	78,794	52,212	4,474	15.4
Jan 5-9/07	7	88	Lower Mainland and Vancouver Island	120,399	22,224	6,306	21	4.7

Source: BC Hydro Winter Storm Report 2006/2007 (2007)

2.15 Methods used to predict tree-related outages

Different approaches have been developed to understand the relationship between fallen trees and outages. A number of authors have developed statistical models. Radmer et al. (2002) used

outage history data along with tree growth, trimming history, and climate data. Xu and Chow (2006) used remote sensing techniques to identify individual tree crowns at risk of interfering with power lines. Hooper and Bailey and Li et al. (2004, 2008), used field measurements of tree characteristics to identify hazard trees along power line corridors, as did Poulos and Camp (2010).

Vegetation growth is often estimated using growth models (Radmer et al. 2002). This technique combined with outage history was used to define an ideal period for vegetation maintenance to avoid local outages. Radmer et al. (2002), criticize the use of growth models and empirical models as a decision tool for vegetation failure rates. They note that these models do not consider pruning in their inputs, which accelerates the growth of new branches. Furthermore, vertical and horizontal growths are closely dependent on the ROW maintenance cycle and that crown diameter for ROW edge trees becomes a function of the last trim date.

Xu et al. (2006), using Duke Energy power outage dataset from South and North Carolina region developed a method that identifies the cause of outage (between tree or animal only) based on circuit information (circuit ID, weather condition, season, time of the day, and number of phases affected). The authors used logistic regression (LR) and artificial neural networks (ANN) to classify the cause of outages caused by trees or animals at the moment the outages occurred. Their goal was to develop tools that would improve field crew dispatch for repair work. If a tree was identified as the probable cause of an outage, the arborist and vegetation management crew were warned so they were prepared in case of dispatch. The dataset was divided in two parts for training (3/4 of the records) and validation (1/4 of the records) of the models. The results showed that both models performed well for both LR and ANN.

Li et al. (2008) applied Culvenor's (2002) remote sensing technique to identify tree crown in power line corridors. The authors found that image spatial resolution, spectral resolution, view

angle, and sun angle were limitations commonly found in all tested approaches. They conclude that this technique is not sufficient for complex sites such as ROWs (which is commonly populated with trees, man-made building, power lines, etc).

Hooper (2003) used light detection and range imagery (LiDAR) associated with computer aided design (CAD) software to identify danger trees along high voltage transmission lines in BC. This technique has been implemented for high voltage transmission lines only as the cost of imagery acquisition is high, according to the author. GIS has been used in the past for windthrow analysis in the forestry context (Talkkari et al. 2000, Mitchell, Hailemariam & Kulis 2001, Lanquaye-Opoku and Mitchell 2005, Scott and Mitchell 2005, Wood et al. 2008) using a variety of spatially represented attributes including stand attributes, soil features, cutblock characteristics, climate data (wind speed/direction, precipitation, and temperature), topographic data (topex, elevation, aspect, slope), and distance from water bodies.

Radmer et al. (2002) models were not able to study the outage location visually, as the dataset used had no spatial component. This was overcome by Xu and Chow (2006), although identification of individual trees is very interesting regarding hazard for the lines, it can be challenging when the grid covers vast areas with complex vegetation component such as BC. (Hooper and Bailey 2004) approach used LiDAR and proved to be very efficient for the 500 kV grid, although the authors pointed out LiDAR dataset covering BC Hydro grid would be a very expensive process. Li et al. (2008) discussed a variety of algorithms used to identify individual tree crowns using remote sensed data to locate hazard trees. The authors emphasized that such a complex vegetated area (e.g. ROW) would require algorithms for each species. This would come at a very high cost. Furthermore, they mentioned the normal issues with remote sensed data (e.g. sun angle, spatial/spectral resolution). Poulos and Camp (2010) were able to identify hazard trees and danger trees. Their method is only useful for small scale projects, as establishing plots along

the whole transmission grid to capture tree features (e.g. height, diameter) would be expensive requiring a great amount of time and financial resources.

2.16 Knowledge gaps and research questions

Previous approaches to outage prediction have performed reasonably well in locating circuits susceptible to tree-related outages. None of these previous approaches has used topographic and climate data. Few of these methods are suitable for predicting outages across extensive systems in heterogeneous terrain and climates, which is the reality for the transmission grid in BC.

In Chapters 3 and 4 I demonstrate how spatial climate, topographic, and stand data along with outage history can be used to develop models to predict the probability of a location experiencing an outage.

3.0 Predicting transmission circuit outage probabilities across British Columbia using topographic and climate data

3.1 Introduction

The BC Transmission Corporation (BCTC) is a crown corporation entirely owned by the Government of BC. It is BCTC's responsibility to ensure that electricity produced by hydro-electric dams and other generating stations arrives in populated areas where it is then distributed by BC Hydro. The hydro-electric dams are mainly located in the BC Interior, while the majority of the consumers are located in the Lower Mainland and on Vancouver Island. Those two areas use about 80% of the total electricity produced in BC.

Connecting generating locations and transmitting electricity across BC is a challenge since the province includes landscapes ranging from forested areas, mountains, glaciers, to river valleys. The transmission grid incorporates 18,000 km of overhead lines and underwater cables, 100,000 wood poles, 22,000 steel towers, and 292 substations (BC Hydro Corporation 2011). Apart from transmitting high voltage electricity, BCTC is also responsible for the operations, maintenance, and planning of the high-voltage electric transmission system within BC (BCTC - Vegetation Management Department 2008).

Disruption of the transmission system has more serious consequences than distribution interruptions as they supply the substations that supply customers. When the transmission grid is affected, it has a cascade effect (Guggenmoos 2007) with loss of power to whole communities rather than a few domiciles. However, the higher voltage components of the transmission grid are relatively robust in the sense that tall poles and steel towers are within wider right-of-ways.

As indicated in Chapter 2, lower voltage transmission lines are more susceptible to tree-related power outages than high voltage lines. Presumably this is in large part because lower voltage lines are located within narrower right-of-ways. Evaluating the role of climate and topographic variables in outage probabilities provides insight into the contribution of these factors to storm damage, and provide BCTC managers with a means of refining line clearance rules and targeting maintenance activities.

3.2 Objectives

The main objective of this chapter is to develop statistical models that would identify factors that contribute to tree-caused outages and predict outage locations caused by trees during wind events. Along with outage data, topographic, and climatic data was used in this analysis.

My research questions were as follows:

1) are tree-related outages localized in clustered patterns, or are they spread randomly throughout the study area;
2) what do locations with higher concentrations of outages have in common in terms of topographic, and climatic conditions;
3) can topographic, and climatic variables be combined to predict the locations of tree-related outages?

A secondary objective of my research program was to produce maps of outage probability and to make recommendations for improved assessment, monitoring, and management of ROWs to reduce the potential for tree-caused outages.

3.3 Hypotheses

The main hypothesis is that topographic and climate variables are useful predictors of the location of the outages caused by trees. A secondary hypothesis is if outages are clustered distributed through the transmission grid. In case of clustered distribution of outages, are they clustered in areas with a higher predicted probability of outages?

3.4 Material and methods

3.4.1 Study area

The transmission grid is distributed throughout the province but the dataset used was limited by the climate data coverage. The climate data was only available for the area ranging from north of the border with the United States (49° 15’ 0’’ N) to south of Vanderhoof, BC (54° 0’ 52’’N) and from east of Bella Coola (126°45 W) to west of ElkFord / BC (114°54’57’’W).

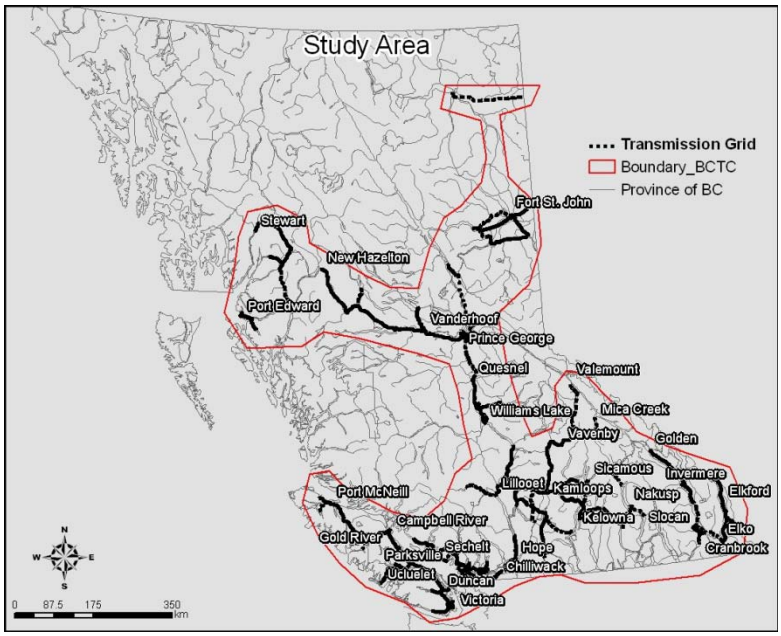


Figure 3.1. The study area is limited within the limits of the red border polygon. The black lines represent the transmission grid.

3.4.2 Outage dataset

The outage history dataset was created from a non-spatial outage dataset provided by BCTC. The outage occurrences are recorded in Distribution Trouble Outage Reports. These reports are completed by the repair crew when attending an outage trouble call. The report has information regarding possible cause of outage, structures affected (e.g. conductor and cables), weather conditions, etc. In the case of a tree-related outage the scene is assessed and a report of the tree attributes such as tree species, age, height, diameter at breast height, location of failure, root conditions, pruning history, and visual defects.

The outage information provided by BCTC for this research was derived from the Control Room Operating (CROW, database used to manage electrical grid and update with post-mortem "Tree Failure Reports" – see A.2) and was provided as a single MS Excel© spreadsheet with one record for each outage during the years 1990 to 2008. The attributes of the outages were stored in columns. Extra information about outage consequences and in some cases updates had been added to this digital dataset. The attributes included: circuit affected, closest substation, number of customers affected, number of customer-hours lost, and time to restore outage. There were no spatial coordinates for the outages, but information regarding the outage location, circuit affected and outage causes was stored in the 'Event Comment' attribute column. A total of 938 outages from 1990 to 2008 were listed in the digital dataset. I have classified these outages in 7 classes based on the Event Comment according to the cause of the outage (Table A.1.). Outages from other causes such as wildlife, car accident, and vandalism were dropped from the database. The tree-related outage class has the records of outages caused by trees but without sufficient description to spatially locate it. The process to create the spatial dataset using the non-spatial outage history is described in Section 3.4.4.

After examining the whole dataset, 237 tree-related (42% of the total tree-related outages) outage records remained with reasonably reliable (+/- 500 m) spatial locations. All of these remaining outage records were on 69 or 138 kV circuits. Higher voltage circuits either experienced very few outages (e.g. 230 kV circuits experienced only 5 outages) or could not be spatially located.

3.4.3 Assets dataset

The spatial datasets provided by BCTC were in vector format (shapefile – *.shp by ESRI®). Shapefiles are a set of files that when combined provide information about the location of the object (e.g. point, line, or polygon) and a set of information associated with the object. Shapefiles of the substations, structures (poles, towers, switches, etc), circuits, and the communities were provided by BCTC. Each of these files contained information including object id, length (for circuits), and closest substations.

3.4.4 Creating the spatial outage dataset

The 'Event Comment' column in the non-spatial dataset (Excel file) provided by BCTC had information describing the outage cause, outage location (e.g. distance from a substation), and structures involved (see Table 3.1 for sample of the non-spatial outage history dataset).

Table 3.1. Sample of the non-spatial dataset. The Event Comment field references to the circuit Id (underlined) and outage location (italic).

Area	Date	Time	Circuit ID	Voltage	Customers Affected	Customers Hours	Event Comment
VIC	6-Jun-08	12:48:22 PM	1L125	138	3101	9498.54	*4.5 km north of KGH substation, tree found on line between two structures. B to C phase faul*
VIC	23-Jul-06	8:05:09 PM	1L127	138	1559	359.44	*Tree on the line A & B phase at 27/6 require clearance in the morning to remove.*
LMC	23-Jan-02	3:04:00 PM	60L018	60	1	0.38	60L18 ko (*BC fault at 4.5 km from SFY)* due tc tree on line and unsuccessful A/R. 60L18 sectionalized at #4 sw to SFY.
LMC	29-Sep-00	12:39:00 PM	60L069	60	10	18.00	60L69 ko (*BC fault at 29.6 km from SQH)* due to suspected tree with unsuccessful rcl. See SDR #113329.
VIC	13-Feb-03	10:51:48 AM	60L129	60	1276	939.99	60L129 ko *(AB fault at 45 km from GCL) due to tree on line at str 41/5 (tree trimmers working in vicinity)*. DTR G1 ko on O/S on loss of 60L129. See Evn #5-42570.
NCC	19-Nov-06	12:18:08 PM	60L339	60	1	9.60	*Tree on line bx 9/2 and 9/3*. Also at 9/3 - a bent pin and wire on X-arm.

Every outage record was manually located according to the information specified in the Event Comment column. Distance between structures and distance from substations were the attributes most commonly used to manually locate the outages in the GIS environment. For example the first row in Table 3.1 reports an outage in the Vancouver Island area that occurred 4.5 km from the KGH substation. A tree was found on Circuit 1L125 between two structures (e.g. poles) resulting in a phase-to-phase fault (B to C). The Excel file was edited so that each remaining record represented an outage point with a known location and each record retained all the information from the respective outage occurrence. Each outage record was assigned a unique Primary ID. The outage locations were then created in ArcMap® (ESRI 2011) based on the Excel file. Each point represented an outage location. The information from the outage history dataset was exported to each specific outage point in ArcMap® (ESRI 2011). The final product is a point feature shapefile with the respective outage locations and outage information.

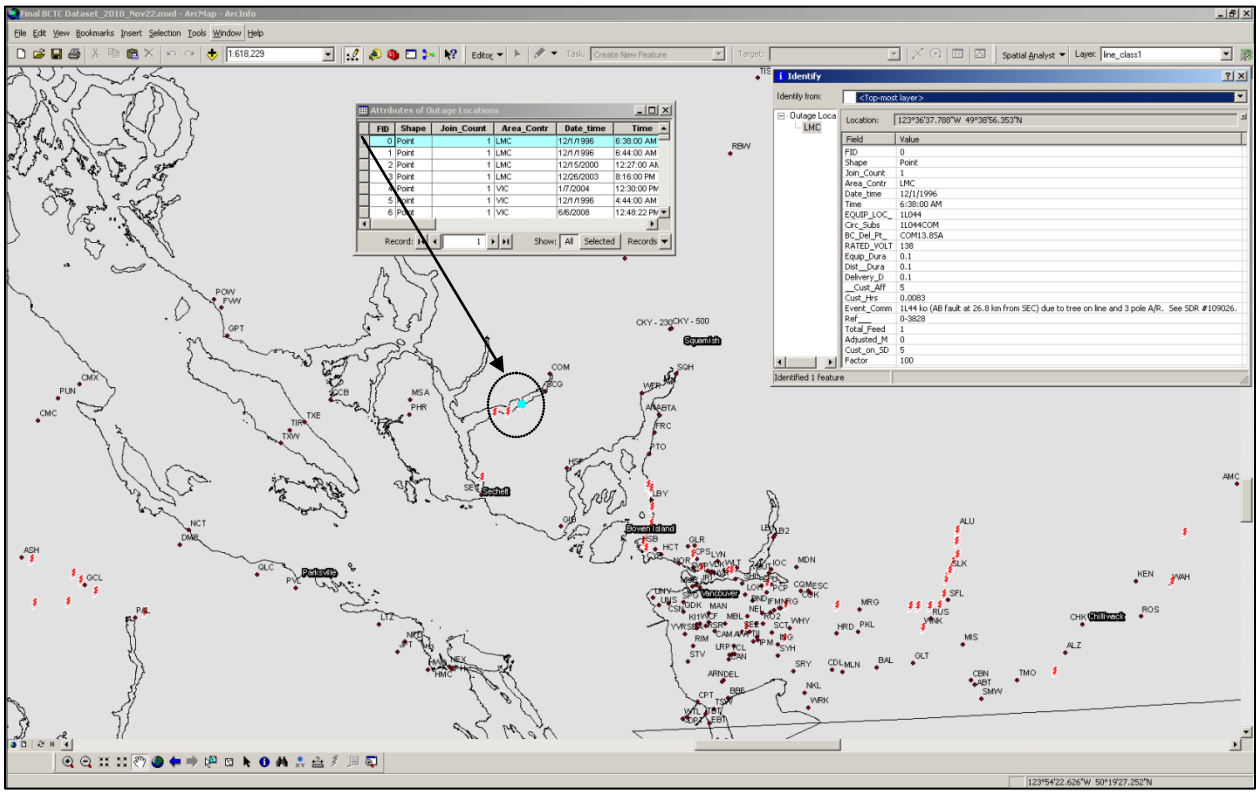


Figure 3.2. Sample of the outage point extracted from the outage history dataset (non-spatial) to ArcGIS® (spatial). The lightning symbols represent the outage locations that were spatially located.

3.4.5 Control point dataset

The purpose of this dataset is to capture the topographic and climatic diversity of the province across the whole transmission network to use for comparison with outage locations, and for subsequent model fitting. This control dataset was composed of a set of data points evenly spaced along the transmission grid. The control point dataset was created using a set of tools and operations from ArcMap® (ESRI 2011). The lines representing the individual circuits in the circuit shapefile were merged together using the Merge tool from Arc Toolbox in ArcMap® (ESRI 2011). This operation is required because evenly spaced points cannot be created in different objects (in this case circuits) requiring all the circuits to be merged as one all-circuit-length line. With this single merged circuit selected the "Divide" tool from the Editor Tool bar was opened, and the "Divide by distance" option was selected. The distance selected was 1 km, so control points were placed every 1km along the whole grid. This 1 km distance was used because it fell within the spatial resolution of the raster and vector variables (25 m topographic grid and 4 km MC2 - see Chapter 2 for definition - point shapefile, respectively) that were to be used as predictors. As the circuit information was needed for the outage analysis, all the information in the original circuits' layer was extracted to the control points. A Primary Id attribute was also created for this dataset so that each control point had a unique ID. For statistical analysis the outage location and the control point dataset were merged. From now on, the term 'observation' will refer to a record in this dataset, whether it is an outage location point or a control point. For more specific information about this merged dataset see (Table A.3).

3.4.6 Topographic variables

Terrain Resource Information Management (TRIM) point elevation maps, were obtained from the Forest Information Resources Management Systems laboratory in the Faculty of Forestry, University of British Columbia with the permission of the Base Mapping and Geomatic Services

Branch, Ministry of Sustainable Resource Management. A Digital Elevation Model was produced from TRIM at 25 m spatial resolution in raster format. Distance limited topographic exposure (Topex) was derived from TRIM dataset, at 25 m spatial resolution and is used in raster format. Each cell has a value that represents the local topographic exposure to wind from any direction. Classical topex is the maximum angle to the skyline in the eight cardinal directions summed to one index. A classical topex score of 0 degrees could represent either a mountaintop or a flat plain. Those two representations experience different exposure behaviours, and therefore they should be treated differently (Quine and White 1998). Topex-to-distance is an adaptation of topex in which angle to ground is measured within a fixed distance (e.g. 2 km) and which allows negative values in any of the eight cardinal directions. This makes it possible to differentiate between hilltops and flat plain (Hannah, Palutikof & Quine 1995). Negative or low values reflect more exposed locations (e.g. hilltops) and positive values reflect sheltered locations (e.g. valley bottom). Topex-to-distance is also more suitable for automated calculation of topographic exposure within a GIS. Topex_2km (2 km distance to skyline) was used in this research. This dataset was provided from Dr. Mitchell's Windthrow Lab archives.

The slope information was derived from the digital elevation model (DEM). In ArcMap® (ESRI 2011), the DEM was converted to slope using the SLOPE tool on ArcCatalog® (ESRI 2011) in a 25 m spatial resolution on a RASTER format. This dataset provides the ground slope experienced within the province and assigned to pixel cells with values ranging from 0 to 89 º. For more specific information about this dataset see (Table A.3).

3.4.7 Climate variables

Spatially gridded information about wind speed, precipitation, and temperature were obtained from Numerical Weather Prediction Models (NWP). Two types of NWP were used in producing

the data used in this analysis: the Canadian Mesoscale Community Compressibility Model (MC2) and the BC Hydro Wind Resource Map.

The MC2 models were run by the UBC Earth and Ocean Science Weather Forecast Research Team (WFRT). The climate statistics were based on hourly forecasts archived over a 5 year period (October 1st, 2004 to September 30th, 2009) and include average hourly wind speed (km/h), average hourly precipitation (mm/h), average hourly temperature (ºC), and top 5 events wind speed (km/h). The data collection started in early October because this is the typical start of the winter storm season. The MC2 simulations were run at a 4 km spatial resolution for the majority of the province (Modzelewski and Bakhshaii 2009). The climate variables used in this study were displayed in a grid format as point shapefiles at 4 km spatial resolution.

The other source of spatial wind speed information was the BC Hydro Wind Energy Resource Map. This map was developed to mainly predict wind speed and directions for an initial assessment of wind turbines as an alternative source of electrical energy, across the province. The information is presented in raster format in 1 km spatial resolution and the annual average wind speed was simulated in meters per second (m/s) (True Wind Solutions LLC 2001). For more specific information about this dataset see (Table A.3).

3.4.8 Extracting information to the outage/control point dataset

The climate and topographic datasets were opened in ArcMap and extracted to the points in the outage/control point dataset using ArcGIS® tools. Each observation took the value of the closest location with available information. No interpolation was used for the data extraction process.

3.5 Assumptions and limitations

The topographic datasets derived from field measurements. Sources of errors are acknowledged as part of the creation process which was done using computer software based on field points

previously collected. As part of the interpolation process, it is assumed that the data used is the best representation of the real data available for this project. As far as climate data used, the source is a product of Numerical Weather Prediction Models, which are simulations produced using real data collected from previous years. Any errors in these previous processes would result in errors in the climate data used. Furthermore, as any simulation process, representing the real world situation is rather difficult and models although not perfect are the closest sources to real world data in a relatively affordable manner.

Modzelewski and Bakhshaii (2009) listed some limitations of MC2. Firstly, the forecast deteriorates with time as predictions eventually start to be based on prediction instead of actual data. They advise that the earlier data is more reliable than latter ones. Benoit et al. (1997) studying the Canadian MC2 model, summarized the limitations of this and other numerical weather prediction models, particularly for simulating specific weather events. There is uncertainty in the initial conditions of the simulated event. A process called initialization is used to avoid that issue. Initialization consists in using data prior to the event. Stull and Nipen (2008) initialize their runs 9 hours previously to the event time to simulate a specific event of interest. In their forecast models, Modzelewski and Bakhsaii (2009) used an initialization period of 3 h. Secondly, the initial conditions for finer scale NWP models (e.g. at spatial resolution of 4 km and less) are derived from much lower spatial resolution datasets (e.g. 108 km); therefore lack of accuracy in the coarser atmospheric circulation models affects the high resolution models. Finally, the representation of elevation in NWP's is with DEM's, but these are smoothed and not always faithful compared to the real terrain (Thompson, Bell & Butler 2001).

For The BC Hydro Wind Resource Map, annual average wind speed derived from the simulations was compared with actual annual average wind speed for climate stations across BC. The sampling error was estimated to be 3.8%, and simulated speeds were on average 12% lower

than measured wind speeds. Sources of error included inaccurate representation of local topography and local surface roughness (True Wind Solutions LLC 2001).

It was assumed that the information in the Event Comment attribute in the outage history dataset was accurately collected. However, since the precision of the distance measurements in the Event Comment field was to the nearest 0.1 km, this limited the mapping accuracy to +/- 0.1 km.

3.6 Experiment design - data export

The outage and control point datasets were merged using the Merge Tool from the Arc Toolbox in ArcMap® after a new variable was created to differentiate outage records from control point records. This new variable was assigned the name “STATUS” and was given a value of 1 for the outage records and value of 0 for the control point records. Gridded topographic variables (elevation, topographic exposure, and slope), and gridded climate variables (MC2 average hourly wind speed, top 5 event wind speeds, average hourly temperature, average hourly precipitation, and BC Hydro wind speed), were extracted using the Extract Value to Point from ArcToolBox to each of the points in the merged outage/control dataset. The resulting database was exported as a *.dbf file using the Export Attribute Table tool on ArcMap® for the statistical analyses. This tool extracted the value from the closest pixel to each of the outage/control points. The circuit data was extracted using the Spatial Join tool. As the vector values are not stored in pixel cells but point vectors (UTM coordinates), the proximity to the closest point was the criteria used for data extraction. Since all the attributes were extracted to all the control points and outage locations, it was important not to have control points and outage locations at the same locations, with identical information. To prevent this, all control points that were within 1 km radius from an outage point were deleted. Also, all control points on circuit segments that travelled under water were deleted.

Climate and topographic raster variables were extracted for the combined outage/control point dataset.

Control points and outage records were verified regarding information carried about the extracted variables. Records with invalid information (e.g. wrong topex data) were fixed or excluded (in case of inaccurate data) from the modeled dataset.

3.7 Statistical analysis

The outage/control .dbf file was imported into SAS (SAS Institute Inc. 2008) using the Import Wizard. This dataset was sorted and the control points were sub-sampled. A sub-sample of the original dataset was created to keep the ratio of 1/3 between outage records and control points and a minimum of 25 events per predictor variable (c.f. Peduzzi et al. 1996). A random generator algorithm was created so records (control points) could be randomly selected. Ten percent of the original control point dataset were kept and merged back to the outage dataset for the following analyses. A total of 201 outage records and 552 control points (total of 753 records). SAS (SAS Institute Inc. 2008) was used for all statistical analyses and model fitting. The statistical analysis was performed using outage and control points from the 69 and 138 kV circuits only because the other voltage systems did not experience enough outages to be analyzed statistically.

3.8 Independent variables

Contingency tables and Chi-square tests (Delwiche and Slaughter 2003) were used to evaluate the relationship between outage frequency and the independent variable of interest. Prior to this analysis, continuous variables such as elevation were divided into classes. Where the Chi-square test was significant, contingency table results were graphed for easier visualization. The resulting graphs reveal any outage frequency trends across the classes of the independent variable, along with the distribution of outage/control points across these classes.

3.9 Logistic regression

Logistic Regression (LR) is an adaptation of linear regression where the dependent variable follows a binomial response (in this study, yes=1, no=0 to the occurrence of an outage). LR is widely used when observational data is used to predict the probability of occurrence of an event as a function of various predictor variables. LR transforms the responses (y) into probability (π) as a function of the variables selected by the model (Bergerud and Ann 1996). The y-value in the linear regression equation $y = a + bx$ is transformed to $logit\ (\pi) = log\ [\pi / (1- \pi)]$ to simulate linear regression. A back transformation of the logit ($\pi = exp\ (logit) / [1+exp\ (logit)]$) is required to calculate the probability of experiencing the event of interest. I used the forward selection method.

Pearson correlations between potential predictor variables were also analyzed as variables that are correlated could be masking the model performance.

The model fitting process usually divides the dataset in two parts. One part to develop the models and the other part to test the model fit. In this study, the outage dataset was too small to be split; therefore, the models were not tested against an independent outage dataset.

3.10 Hosmer and Lemeshow goodness of fit

The Hosmer and Lemeshow Goodness of Fit (HL) test sorts all the observations according to their predicted probability scores, places the sorted data into 10 equal size groups, and then uses a Chi-square test to compare the average observed number of outages with the average predicted probability of outage for each group. The critical HL Chi-square value for a 10 class analysis is 15.5073 (the lower the better). The ratio in proportion to outages between the 10th group and the 1st group indicates how well the model differentiates between the highest and lowest probability groups.

3.11 C-statistic and concordance/discordance

The c-statistic ranges from 0 to 1 and is a measurement of the discriminative power of a predictive model. It is calculated as the proportion of all possible pairs of subjects (outage and no-outage) in which the predicted probability is higher for the outage than the non-outage member of the pair (Westreich et al. 2009). Numerous iterations (number of pairs) are run until the c-value is assigned a value. A model that was as good as a coin toss, on average, would produce a c-value of 0.5. The higher the ratio the better the model. The percent of concordance, percent of discordance, and percent of tied values discriminates the c-value calculation.

3.12 Mapping the probability of outages

For selected logistic regression models, maps displaying the probability of outage for specific locations were created. A shapefile with control points and outage locations having all the variables used in the model fit was used for mapping the probability of outages for each location. The models are equations produced by the logistic regression. New columns were created in the shapefile to accommodate the models (equations). This process consisted in adding two new attribute columns to the model shapefile attribute table in ArcMap® and running "The Field Calculator" for each of the columns. The first column stores the logit (see Section 3.9) based on the values of each of the selected variable for each record location. The second column converts the logit in to probability of outage for that record location.

3.13 Outage density

The outage probability maps were compared visually with the pattern of outages, and with an outage cluster map, line cluster map, and outage density map. Outage cluster reflects the concentration of outages within a specific area. Line cluster displays the concentration of lines

within a specific area. Outage density is a measurement of the number of outages per length of circuit. The processes of creating these maps are described in Appendix B.

3.14 Google Earth

An exploratory analyzes was performed on GoogleEarth©. I looked at transmission lines (files provided by BCTC) in different places of the province and measured the ROW width for lines of different voltages using the Ruler tool. A total of 6 circuits were randomly measured. They were selected based on their location and voltage (e.g. forested areas and high voltage). The purpose of this analysis was to provide an idea of the ROW width for the different voltage transmission lines as field data regarding ROW width was not collected. Measurements were taken to the decimal level of a meter (e.g. 113.5m). This analysis was purely informative with no statistical component.

3.15 Field inspection

Transmission lines in the vicinity of Pacific Spirit Park (UBC), North Vancouver, Cypress Mountain, and Duncan (Vancouver Island) were visited in the company of BCTC and BC Hydro vegetation management staff. Circuits in these locations had a history of tree-related outages during storms. BCTC staff walked us through the ROWs providing details about vegetation management, pruning and other aspects of vegetation management as well as the treatment history of these particular ROWs along with general line and ROW design issues.

3.16 Results

3.16.1 Google Earth

Viewing the transmission grid in GoogleEarth© (2011) it was apparent that higher voltage transmission lines are within wider ROWs (65 to 90 m). Occasionally two circuits were placed in

the same ROW resulting in wider clearance (200 m). The 500 kV circuit examined had 16 m between phases, the 230 kV had 8 to 10 m, and the 69 kV had 1.3 m. The sites visited in the North Shore (Cypress and Capilano Substations) were located in forested areas with tall trees adjacent to the ROWs. The lines were placed in steep areas both parallel and perpendicular to the slope. From GoogleEarth© (2011), the ROW width ranged from 17 to 35 m (Table 3.2). The circuit in the Cypress Mountain runs perpendicular to the slope and tall trees were present in both sides of the ROW representing hazard to the line as trees were well in the range of reaching the line in case of being windthrown (Figure 3.3). A variety of species were found, including Douglas fir, hemlock, and western red cedar. According to the non-spatial dataset it left 1915 customers without power and a total of 6380 customer- hours lost during the 21st of November of 2006 storm.

Figure 3.3. Cypress Mountain 69 kV circuit.

Source: Wolf Read

The 300 kV lines perform short distance transport for the electricity, such as connecting terminal and substations, usually connecting buildings over short distances in non-forested terrain.

GoogleEarth© (2011) measurements show (Table 3.2) that high voltage circuits have wider ROW width. Some circuits share ROW (e.g. Sea to Sky Hwy) and are placed in wider corridors.

Table 3.2. Sample of Right-of-Way width measured using GoogleEarth©.

Voltage (kV)	Right-Of-Way width (m)
69	17 - 35
138	27 - 52
230/500	47 - 122
Shared	80 - 130

Note: No statistical analyses were performed.

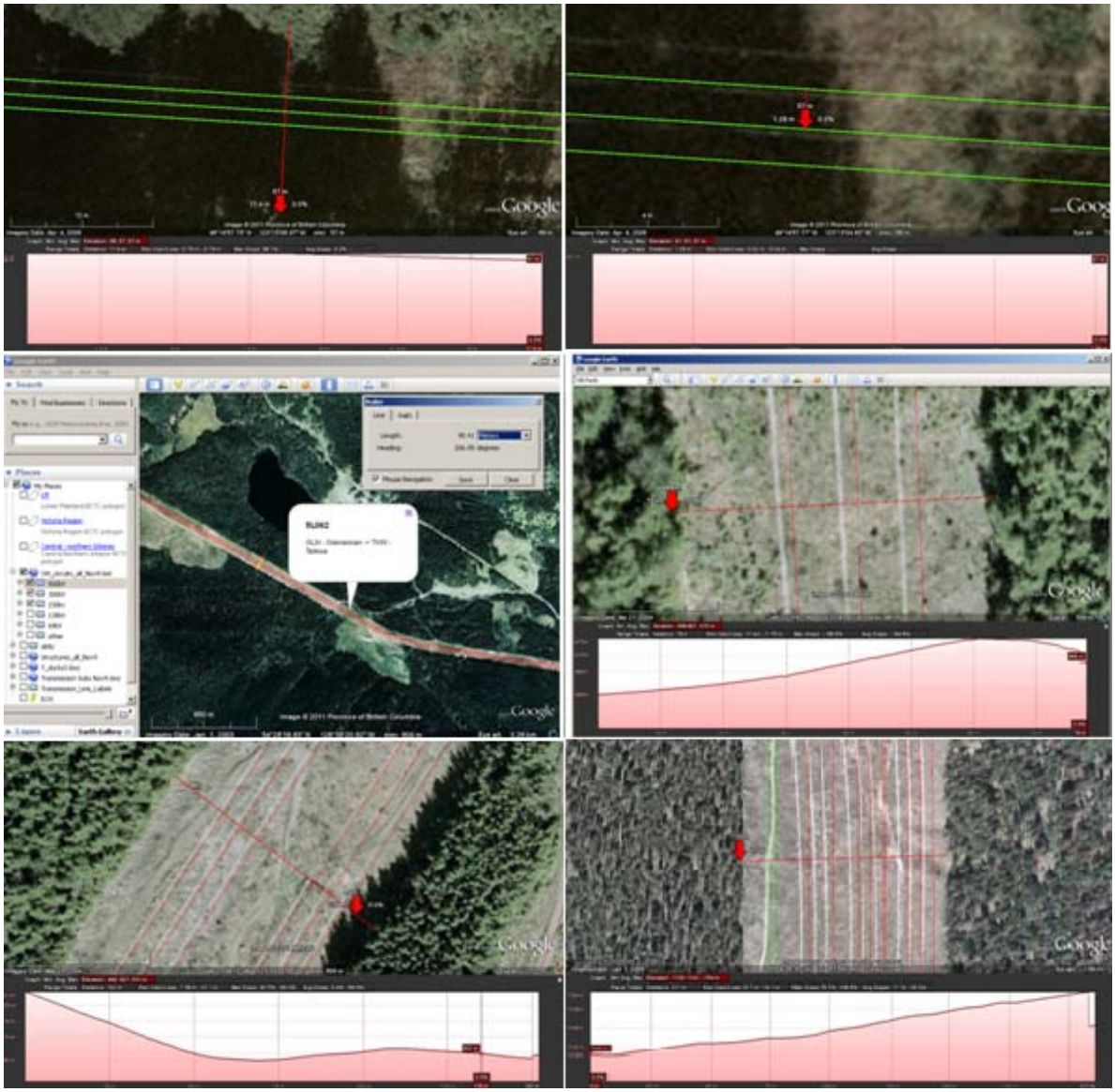


Figure 3.4. Transmission ROWs sizes from different voltage systems. The profiles display the ground slope of the ROW width. Source: ©GoogleEarth, ©2011 DigitalGlobe, ©2011 Cnes/Spot Image, © 2011 Province of British Columbia, ©GeoEye, ©IMTCAN.

3.16.2 Most common causes of outages

Examining the original non-spatial outage dataset, it was found that tree-falls were responsible for most of the outages (62%), followed by 'others' (27%), snow (5%), fallen branches (4%), weekend logger (2%), and wildlife – primarily beavers (1%).

3.16.3 Outage trends throughout the year

There were more outages during the winter months (Figure 3.5). The four winter months (November, December, January, and February) experienced a total of 325 tree-related outages (total of 567), more than half of the total outages. The fewest outages occurred during the spring and summer months (April to August).

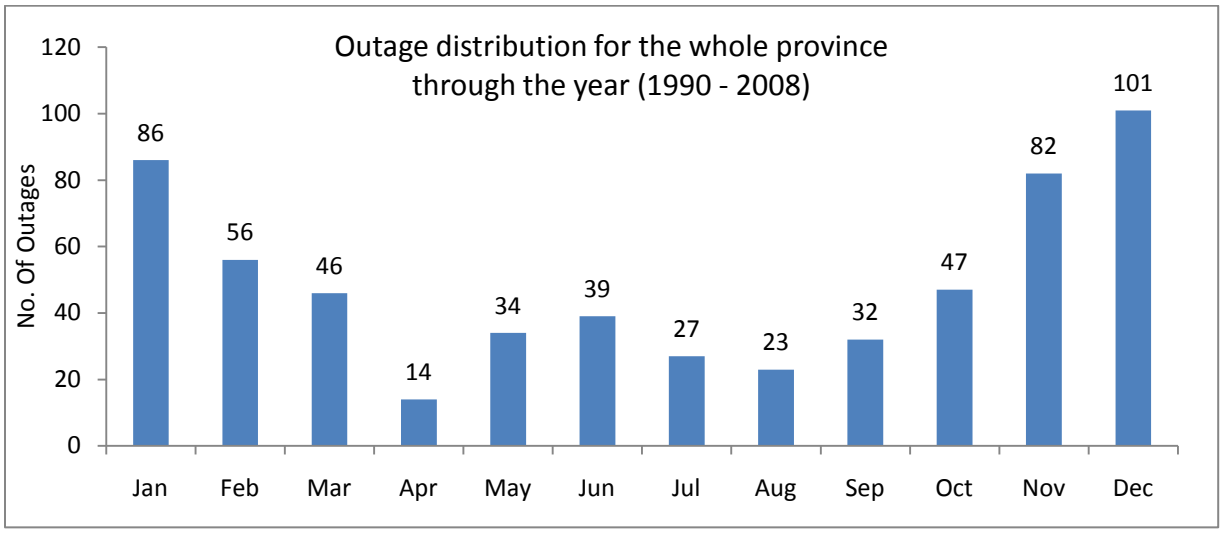


Figure 3.5. Distribution of outage frequency for the whole province by month for the period of 1990 to 2008

3.16.4 Outage by region

There were more outages in Coastal regions, including the Lower Mainland (LMC) and Vancouver Island (VIC) than other parts of the province, particularly during the winter season (Figure 3.6). The Northern Interior (NCC) and Southern Interior (SIC) outage frequency did not vary much throughout the year. All regions experienced a low number of outages (less than 10) during August.

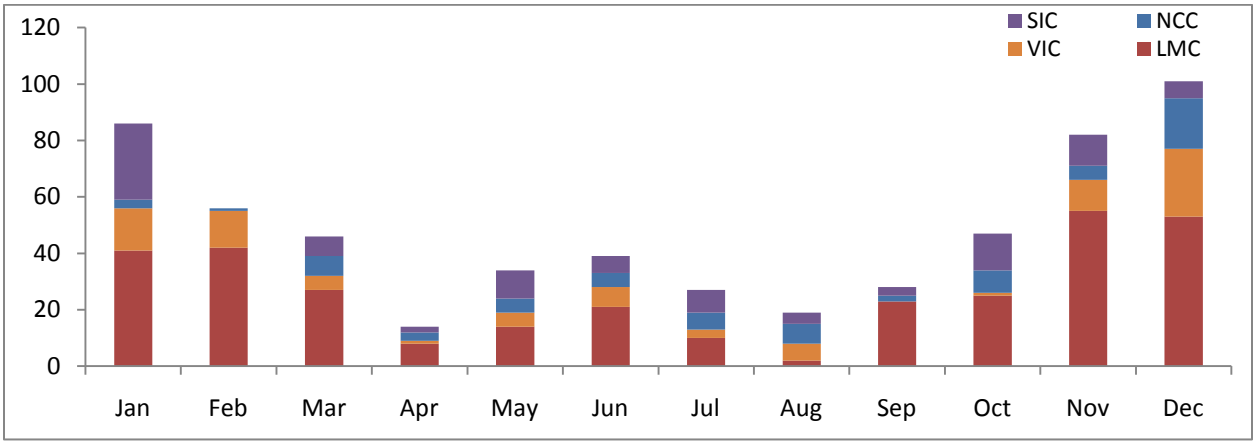


Figure 3.6. Tree-related outage distribution per region by month (a total of 567 records collected from the period of 1990 to 2008). Lower Mainland (LMC), Northern Interior BC (NCC), Southern Interior BC (SIC), and Vancouver Island (VIC).

3.16.5 Outages per year per region

The highest number of tree-related outages occurred in 1999 of which 43% occurred in the LMC (Figure 3.7 and Figure 3.8). The fewest outages occurred in 1992. In general high-damage years were followed by low damage years (e.g. 1999, 2004, and 2006). This could be a random anomaly, but it could also reflect improvements in the vegetation management or that the stormy weather in the previous year had already taken down the most vulnerable trees.

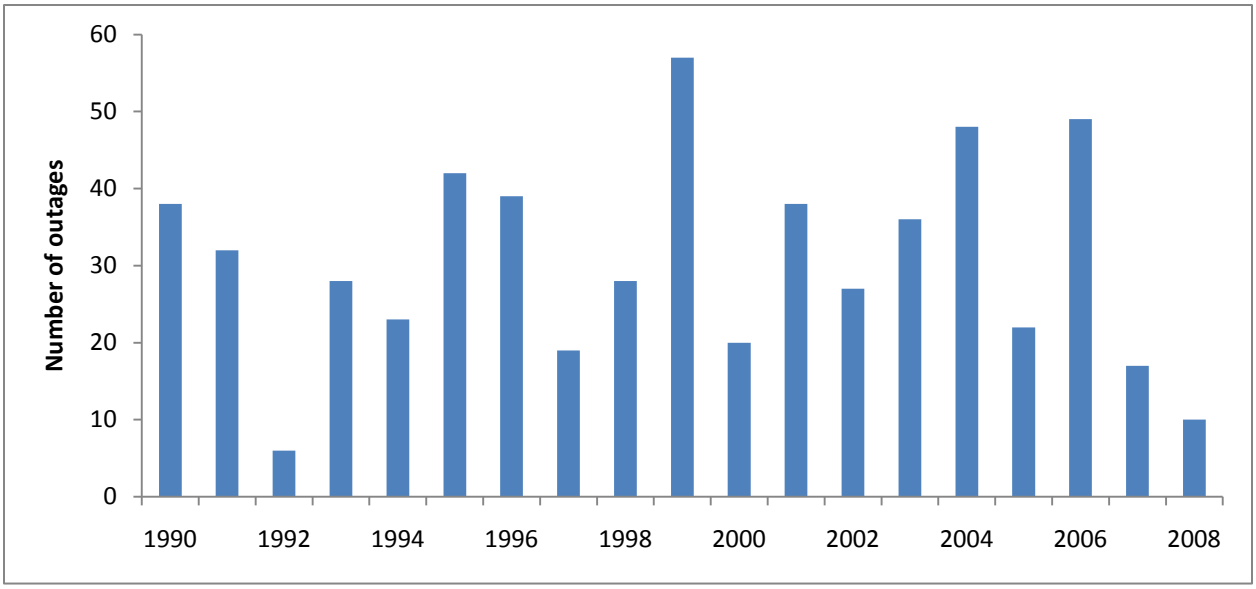


Figure 3.7. Outages per year (N=567). The years following major outage years experienced low number of outages.

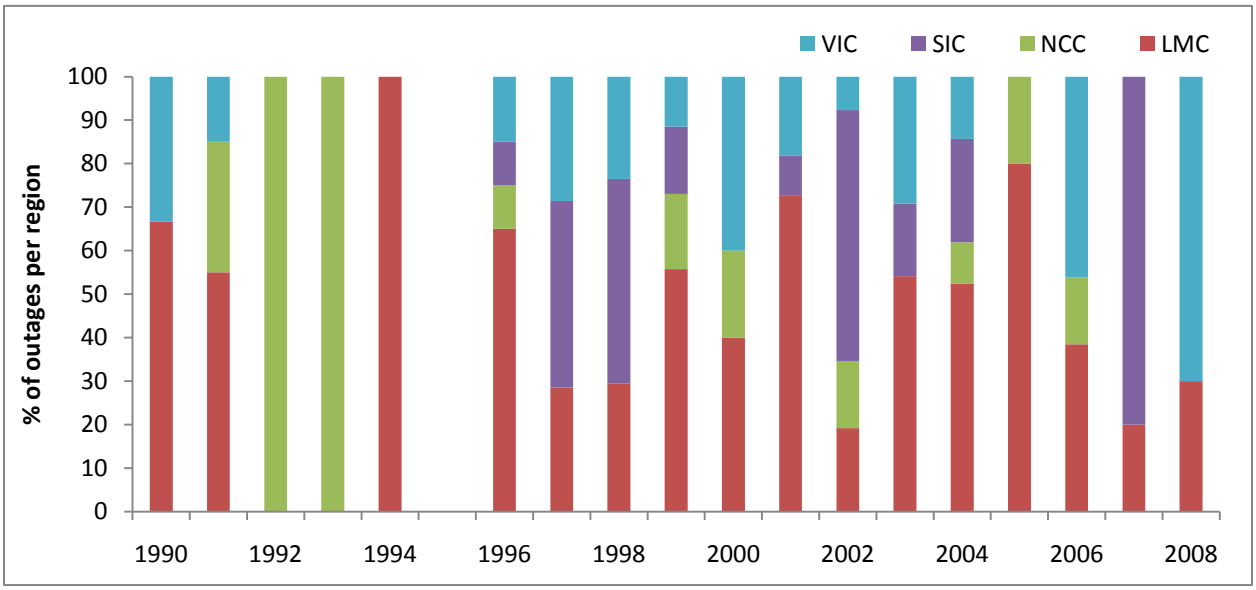


Figure 3.8. Percentage of outages by region. The areas in the graph are Lower Mainland (LMC), Northern Interior BC (NCC), Southern Interior BC (SIC), and Vancouver Island (VIC). LMC and VIC were the regions most affected by outages.

3.16.6 Outages per voltage

The 69 kV grid experienced more outages than the other two grids. The 230 kV grid was the less affected by tree-related outages than the other two voltage grids. The 138 kV grid had more length of lines affected by outages than the other two voltage grids.

Table 3.3. Number of circuits affected, total length of circuits per voltage, outage density per line of voltage based on the identifiable outages pulled from the non-spatial dataset.

Voltage	# of outages	% of outages	No. Of Circuits	Length (km)
69	203	77	239	9,908
138	49	18	156	13,659
230	13	5	96	10,358

3.16.7 Outage per length of line for each region

Circuits located in LMC experienced more outages/km than in the rest of the Province of BC, for all voltage classes (Table 3.4). The 138 kV circuits located in the Southern Interior (SIC) experienced more outages than in the LMC. The VIC region experienced no outages for the higher voltage transmission lines.

Table 3.4. Density of outages per length of line for each region and voltage for BC.

		Outage Density per Region (outage/km)				
Voltage	Number of Outages	LMC	NCC	SIC	VIC	Total
69	203	0.028	0.006	0.015	0.000	0.021
138	49	0.005	0.002	0.005	0.000	0.004
230	13	0.003	0.000	0.000	0.000	0.001

Procedure: the outages were identified and sorted in the non-spatial dataset. Then the circuits' lengths were sorted and summed by voltage and region in ArcMap®. The final step was to divide the number of outages by the length of circuits for each voltage within each region.

The outages were concentrated in the Lower Mainland and a few other locations (e.g. Elkford, Cranbrook, Ucluelet, and Port Edward, Vanderhoof, Kamloops, and Slocan - Figure 3.9 and Figure 3.10). The outage density distribution is similar to the outage clustering, but limited to fewer areas (e.g. Vanderhoof, Sechelt, Parksville, Lower Mainland, and Kamloops among others, Figure 3.12). These clustering and outage density results also indicate that there are a few circuits and locations that experience much higher levels of outages.

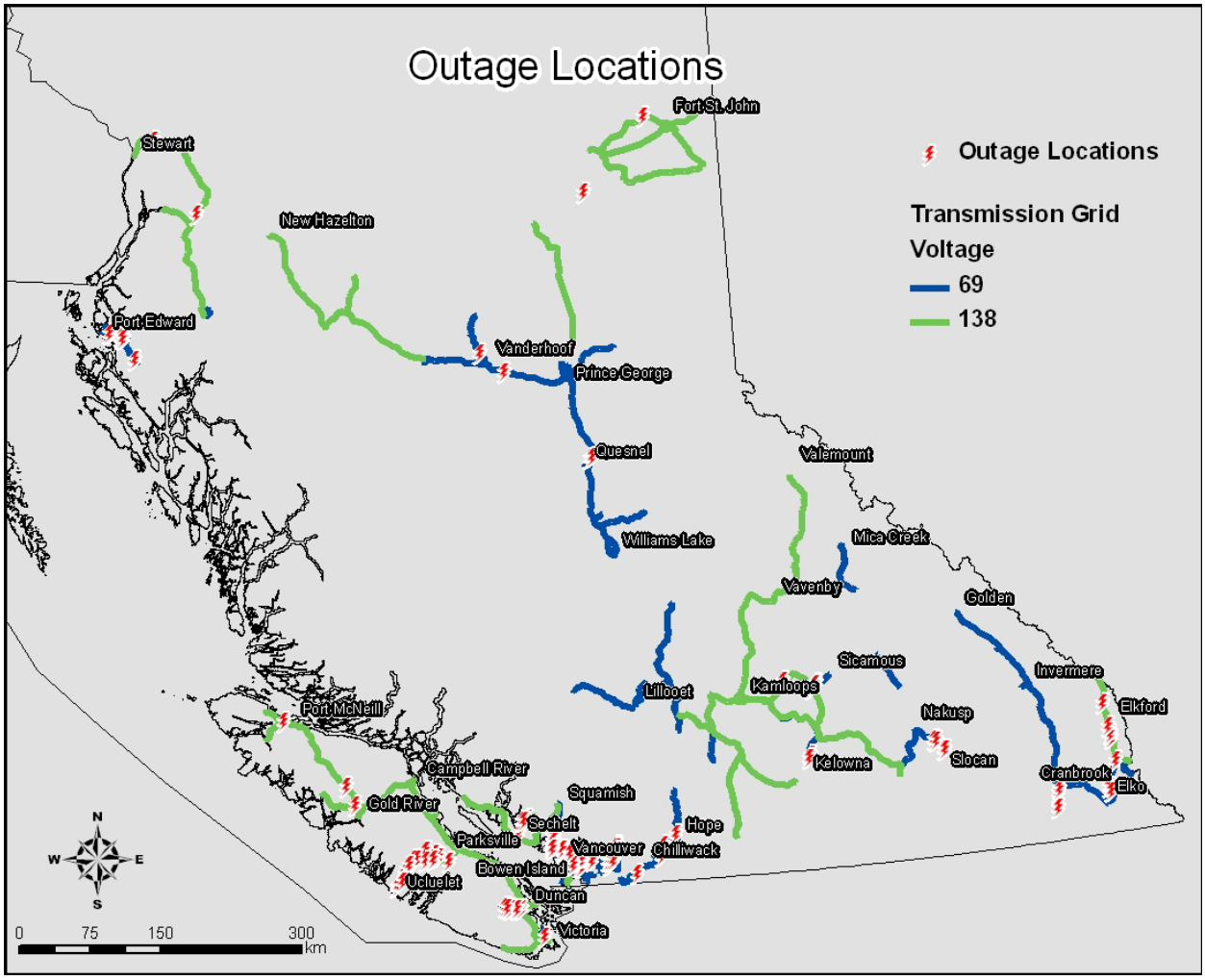


Figure 3.9. Map of the outage locations where voltage lines are displayed with different colours (blue for 69 kV, green for 138 kV). The lightning markers represent the outage locations.

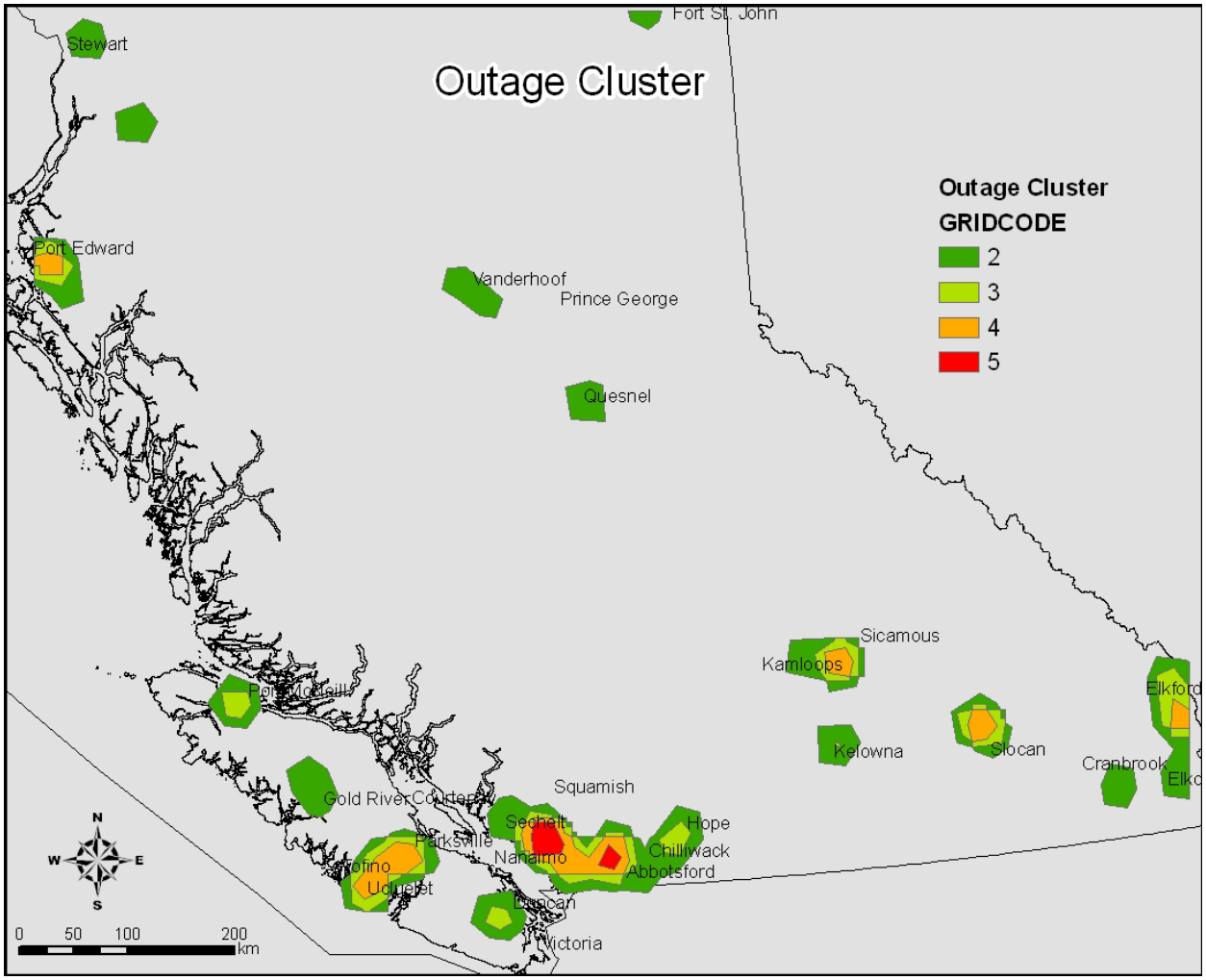


Figure 3.10. This map shows the concentration of outages within a specific area represented by the polygons. The dark and the light green polygons reflect areas of low density and the orange and red polygons reflect areas of high density of outages.

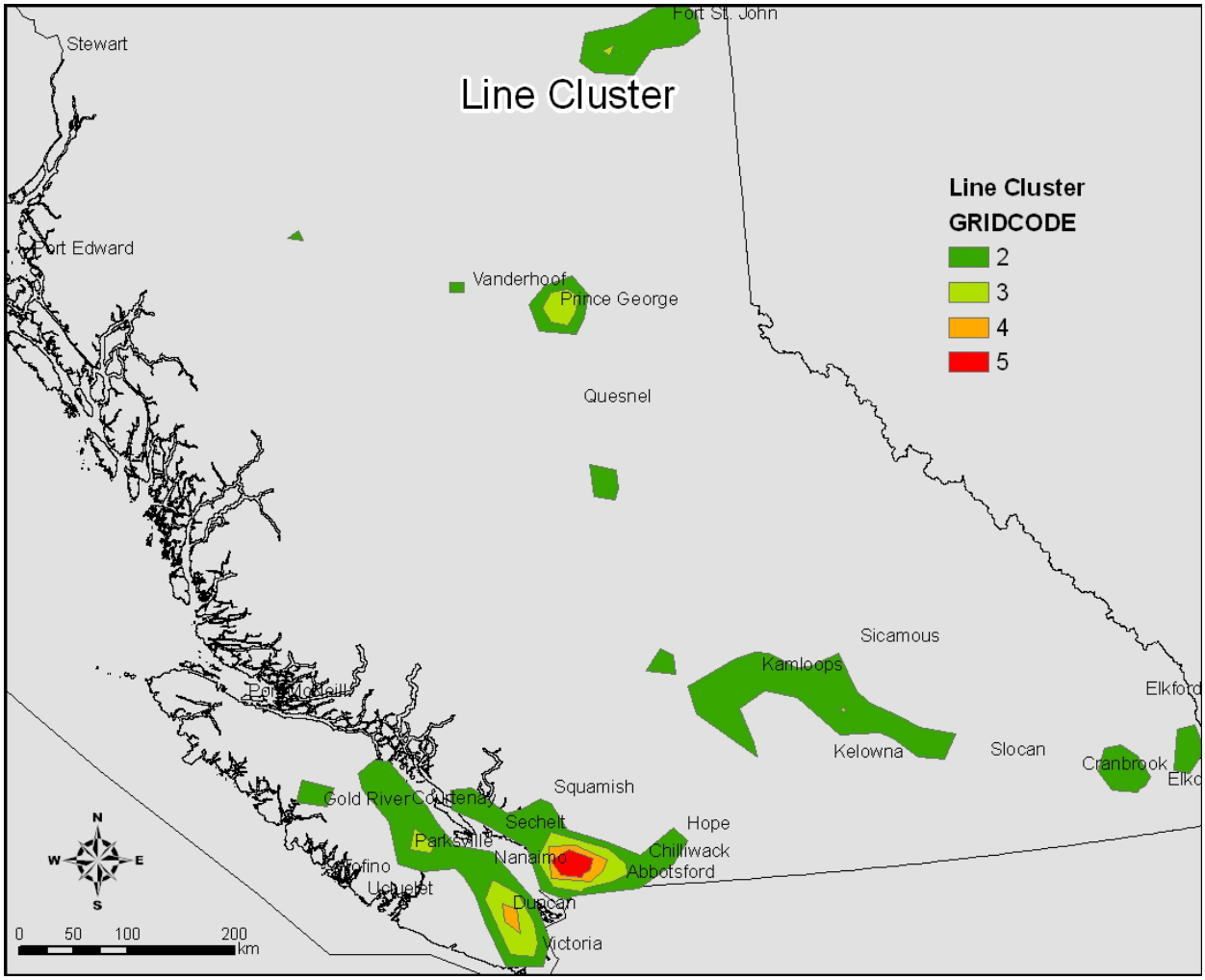


Figure 3.11. This map shows the concentration of lines within a specifc area represented by the polygons. Dark and light green polygons cover areas with lower density of lines per unit of area. The orange and red polygons are areas of high density of lines per unit of area.

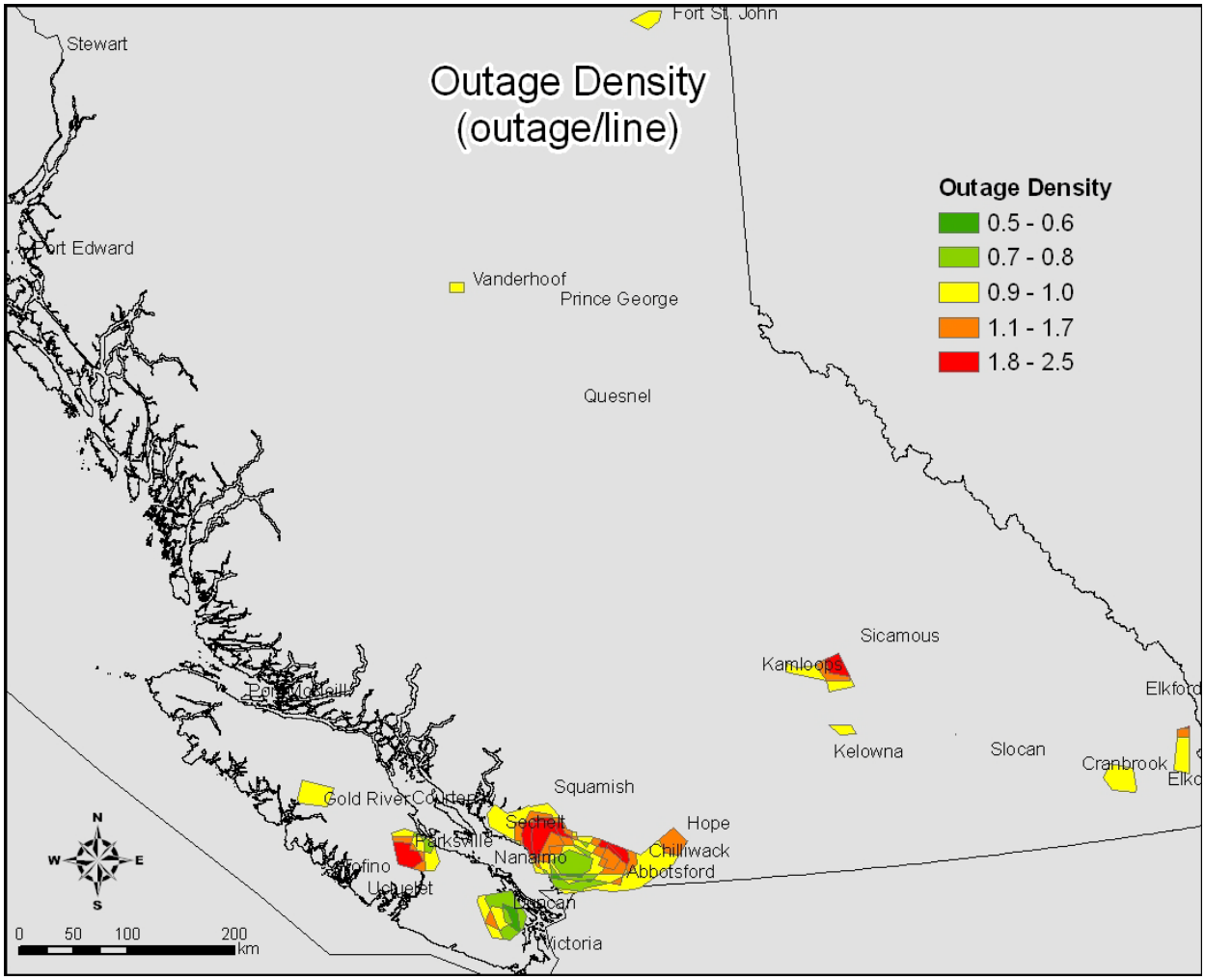


Figure 3.12. Polygons represent the density of outages per length of lines. Dark and light green and yellow polygons are areas that experienced less or one outage per unit of length (km) of line. Polygons coloured in orange and red represent areas that experience more than one outage per unit of length (km) of line.

3.17 Statistical results

High outage density circuits were located in relatively sheltered low elevation and flat areas (Table 3.5). Wind speed and precipitation for these locations were mild compared to the whole transmission grid. The temperature was above the mean for the high density locations.

Table 3.5. Topographic and climate information of the high density outage locations in BC and the sub sample dataset.

	High Density areas[1]			BC			Subsample[2]		
Variables	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Topographic Exposure (°)	46.21	-3.45	211.72	47.93	-10.44	256.09	52.23	-3.45	211.72
Ground Elevation (m)	294.24	0.00	1883.00	497.34	0.00	1923.00	438.16	0	1883
Ground Slope (°)	7.81	0.00	59.75	8.53	0.00	59.75	9.12	0	59.75
Top 5 Events Wind speed (km/h)	7.96	2.24	20.42	7.56	2.20	20.42	7.92	2.24	20.42
Average Hourly Wind speed (km/h)	5.18	1.85	14.06	5.31	1.69	15.03	5.05	1.85	14.06
BCHydro Annual Average Wind speed (m/s)	3.25	1.08	7.19	3.38	1.08	7.20	3.36	1.09	7.19
Average Hourly Temperature (°C)	8.65	-0.16	11.90	7.55	-0.16	11.94	7.74	-0.16	11.9
Average Hourly Precipitation (mm/h)	0.17	0.06	0.51	0.13	0.05	0.52	0.16	0.06	0.51

[1] n=2226, [2] n=753

3.17.1 Correlation between independent variables

Table 3.6 shows the correlation between independent selected variables. There was a good correlation between topex_2k and average hourly wind speed, and a strong correlation between average hourly temperature and elevation. The correlation between elevation and average hourly precipitation was moderate and negative, as was the correlation between slope and average hourly wind speed. There was a strong correlation between ground slope and topographic exposure. Weak correlation was found between elevation and topographic exposure. BC Hydro average hourly wind speed was moderately correlated with MC2 average hourly wind speed.

Table 3.6. Pearson correlations between potential predictor variables, correlation coefficients

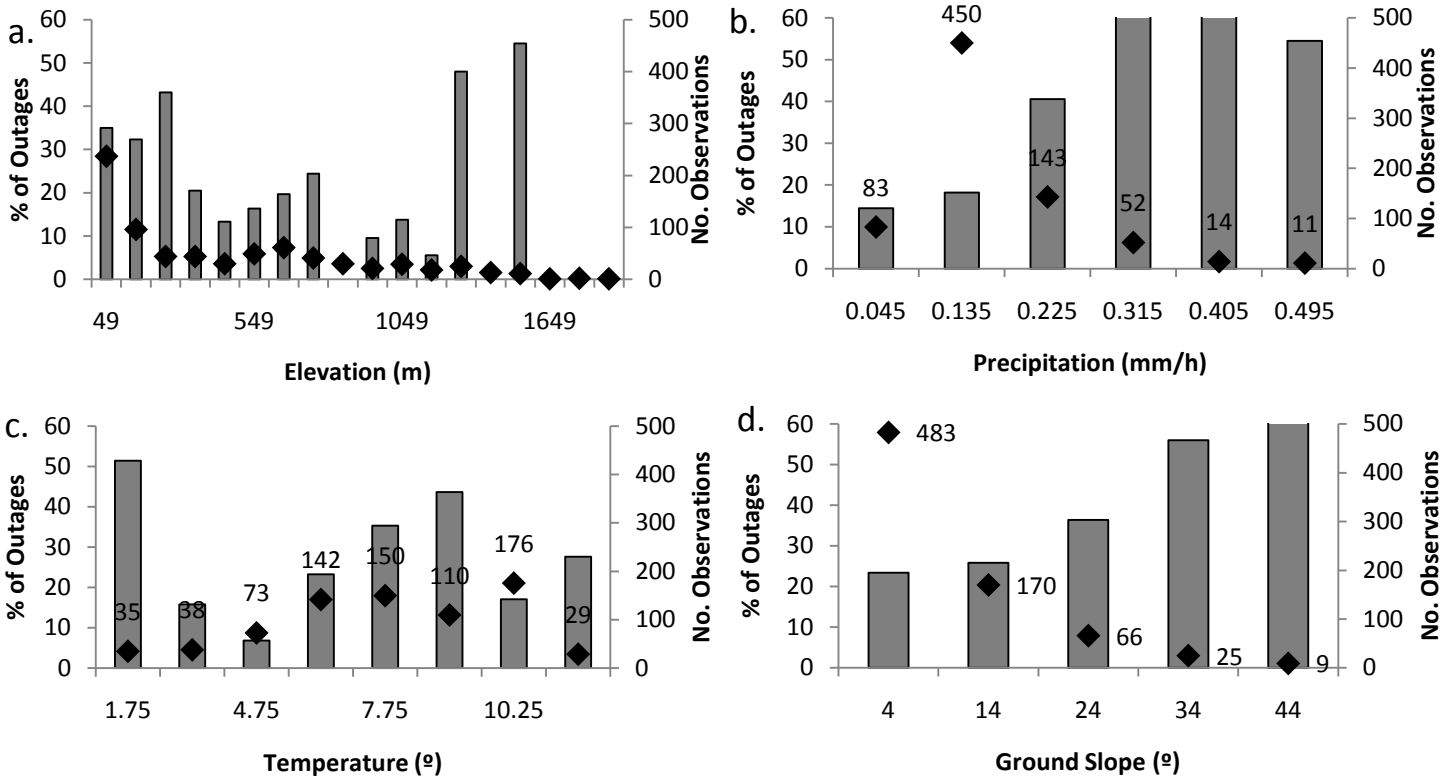
	APCP	MWS_ANNUAL	AVGT	WS_5Y	BCH_WS	TOPEX_2K	ELEVATION
MWS_ANNUAL	-0.38						
AVGT	0.15	0.26					
WS_5Y	0.21	ns	0.07				
BCH_WS	ns	0.49	ns	ns			
TOPEX_2K	0.41	**-0.62**	-0.16	0.26	-0.11		
ELEVATION	-0.43	ns	**-0.84**	-0.27	0.14		
SLOPE	0.30	-0.41	-0.13	0.21	-0.11	**0.69**	ns

Results are given as 'ns' where the correlation is non-significant correlation (*P>0.05*). Values in bold reflect strong correlation between variables

APCP = average hourly precipitation from MC2 model, MWS_ANNUAL = average hourly wind speed from MC2 model, AVGT = average hourly temperature from MC2 model, WS_5Y = Top 5 events wind speed from MC2, BCH_WS = BC Hydro annual average wind speed, Topex_2k = Topographic exposure.

3.17.2 Relationship between outage frequency and predictor variables

Outages were most frequent at lower and higher elevations (Figure 3.13). Outage frequency increased as precipitation increased. Areas with steeper slopes experienced higher outage frequencies than flatter areas. There was a weak trend to increased outage frequency in more topographically sheltered areas such as valley bottoms. There was a decrease in outage frequency as mean wind speed increases. On the other hand, outage frequency increased as the extreme event wind speed increases.



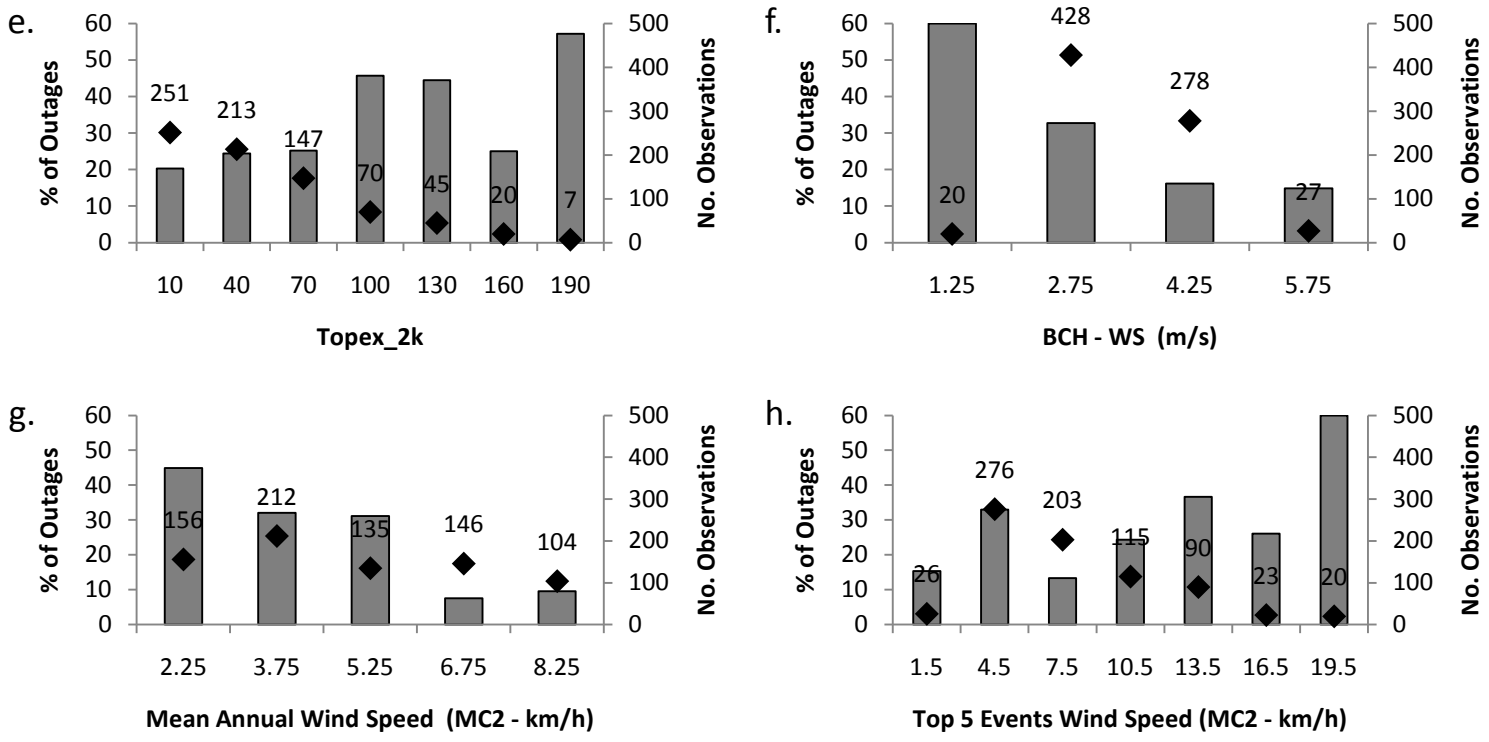


Figure 3.13. Bar graphs showing the frequency of outages for the climate and topographic variables. Diamonds are the total number of observations (control points and outages), the bars are the percentage outage observations or each class of each climate or topographic variable.

Two series were used in this type of graph. The first series plots the percentage of points which are outages for each class of the independent variable (bar graph). The second series plots the total number of observations (e.g. outage locations and control points) for each of the classes of the independent variable.

3.18 Models

A number of models were fitted using logistic regression. Three models were selected and these were: climate variables only (Model 1), topographic variables only (Model 2), and both climate and topographic variables (Model 3; Table 3.7).

The climate only model had the highest c-value of all models and included hourly average precipitation and BC Hydro annual average wind speed. The topographic only model had a relatively low c-value but the lowest HL chi-square. The variables selected in Model 2 were elevation and ground slope. Model 3 with climate and topographic variables had a good c-value

and a relatively low HL chi-square. The variables used for fitting were MC2 hourly average wind speed, hourly average precipitation, and slope.

Table 3.7. Models Summary

Models	Model 1 Climate	Model 2 Topographic	Model 3 Climate and Topographic
Intercept	0.0219	-1.0708	-1.2302
MWS_ANNUAL	ns	-	-0.2398
APCP	11.1383	-	7.6846
AVGT	ns	-	-
BCH_WS	-0.926	-	-
WS_5Y	ns	-	-
Elevation	-	-0.00081	-
Topex_2k	-	ns	-
Slope	-	0.04	0.0011
c-value	0.778	0.624	0.757
concordance	77.6	62	75.5
HL Goodness of Fit	16.9937	15.7631	16.0569
n(out+control points)	753	753	753

n=753, number of iterations = 110952

The Logistic Regression produces the logit, which is transformed in to probability values for each specific location using the equation:

All the three models performed relatively well in discriminating lower and higher risk groups (Figure 3.14). Statistically, Model 2 had the best HL chi-square. Model 1 covered a wider range of values between lower and higher risk groups. The best overall model fit (lowest HL Goodness of fit) was achieved by model 2, discriminating lower risk groups from higher risk groups. All the three models presented a near 1 to 1 relationship between observed percent outages and average predicted probability for each of the 10 groups created by the Hosmer-Lemeshow test.

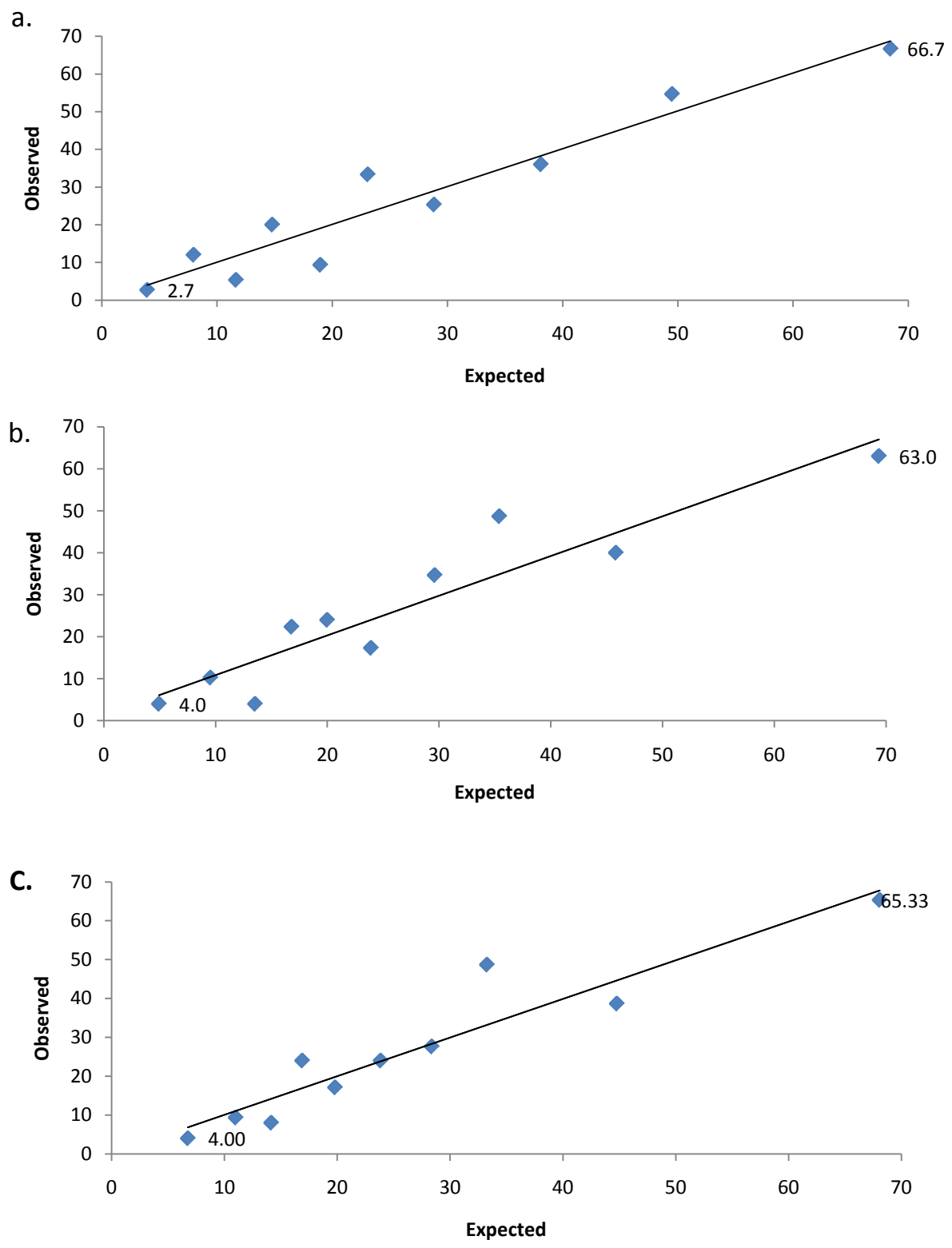


Figure 3.14. Hosmer and Lemeshow Goodness of Fit plot. The three tested models had their partition test plotted in this figure where graph a., b., and c. refer to model 1 (Climate Variables), 2 (Topographic Variables), 3 (Climate and Topographic) respectively.

3.19 Map of the selected models

The three models (Figure 3.15, Figure 3.16 and Figure 3.17) predicted high probability of outages (> 60 % probability of a location experiencing an outage over an 18 year period) for the circuits in the vicinity of Gold River (1L131, 1L134 and 1L120) and Ucluelet (60L129). Other areas with high (> 60 %) probabilities of outages included: Sechelt, Squamish, Vancouver, Chilliwack, Nakusp, Sicamous, Vavenby, Invermere, and Golden. Most of these areas are in mountainous terrain and are heavily vegetated. The outage density analysis (Figure 3.12) visually confirms the model performance as these same areas had high outage densities per length of line.

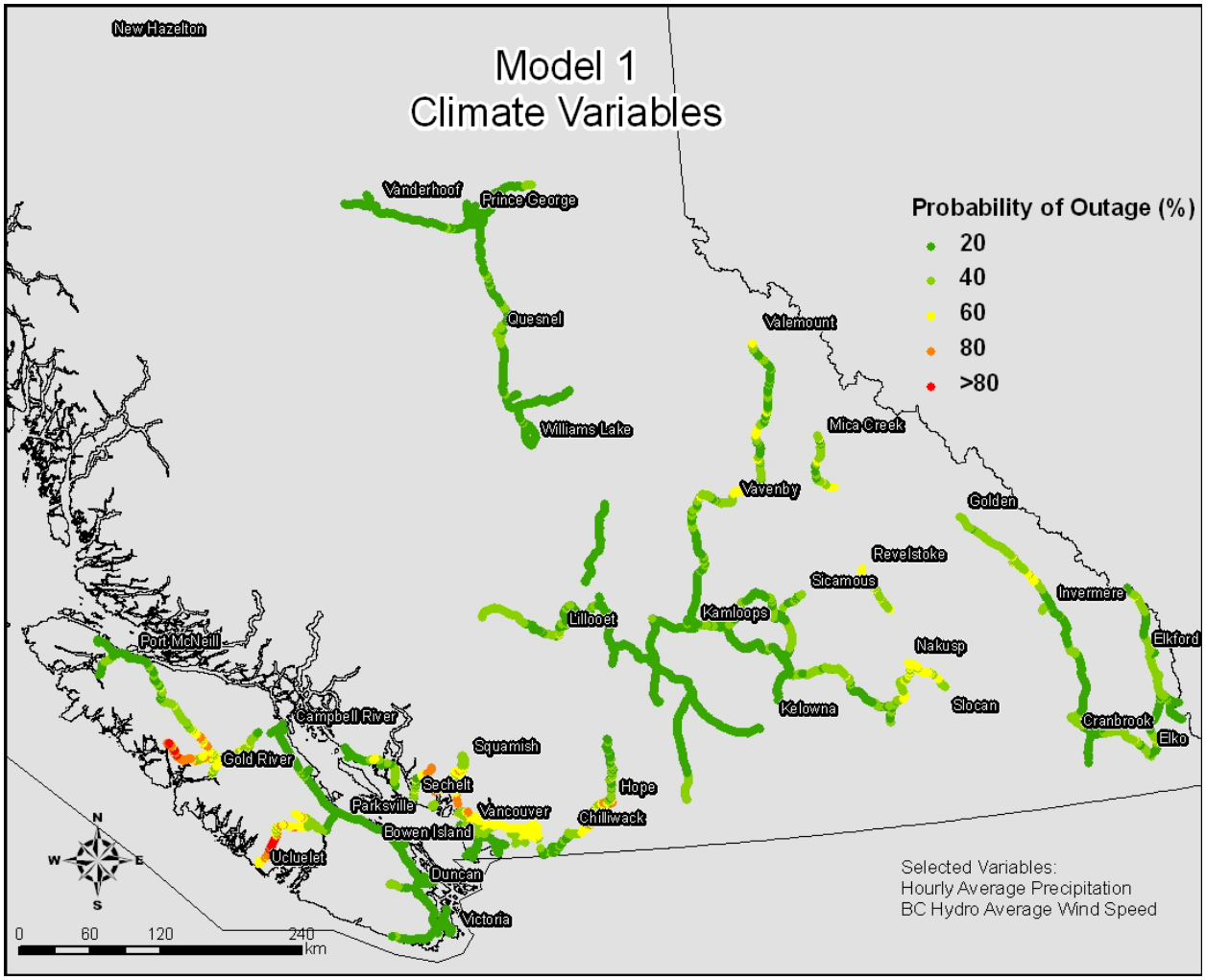


Figure 3.15. The map displays the probability of experiencing an outage according to model 1 using hourly average precipitation and BCH annual average wind speed as predictors. Circuits coloured in dark and light green were predicted to experience fewer outages than circuits coloured in yellow, orange and red colours.

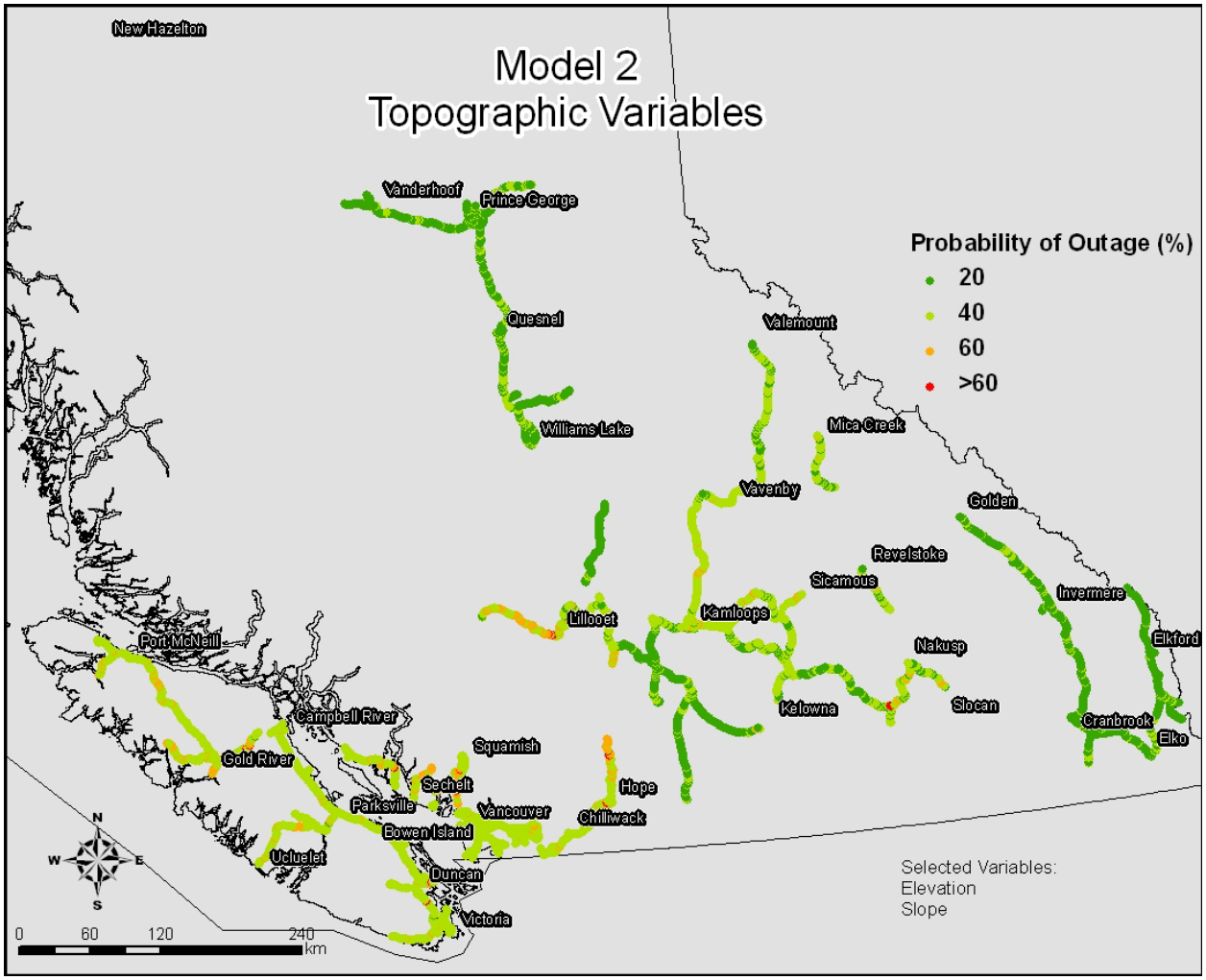


Figure 3.16. The map displays the probability of experiencing an outage according to model 2 using elevation and ground slope as predictors. Circuits coloured in dark and light green were predicted to experience fewer outages than circuits coloured in orange and red colours.

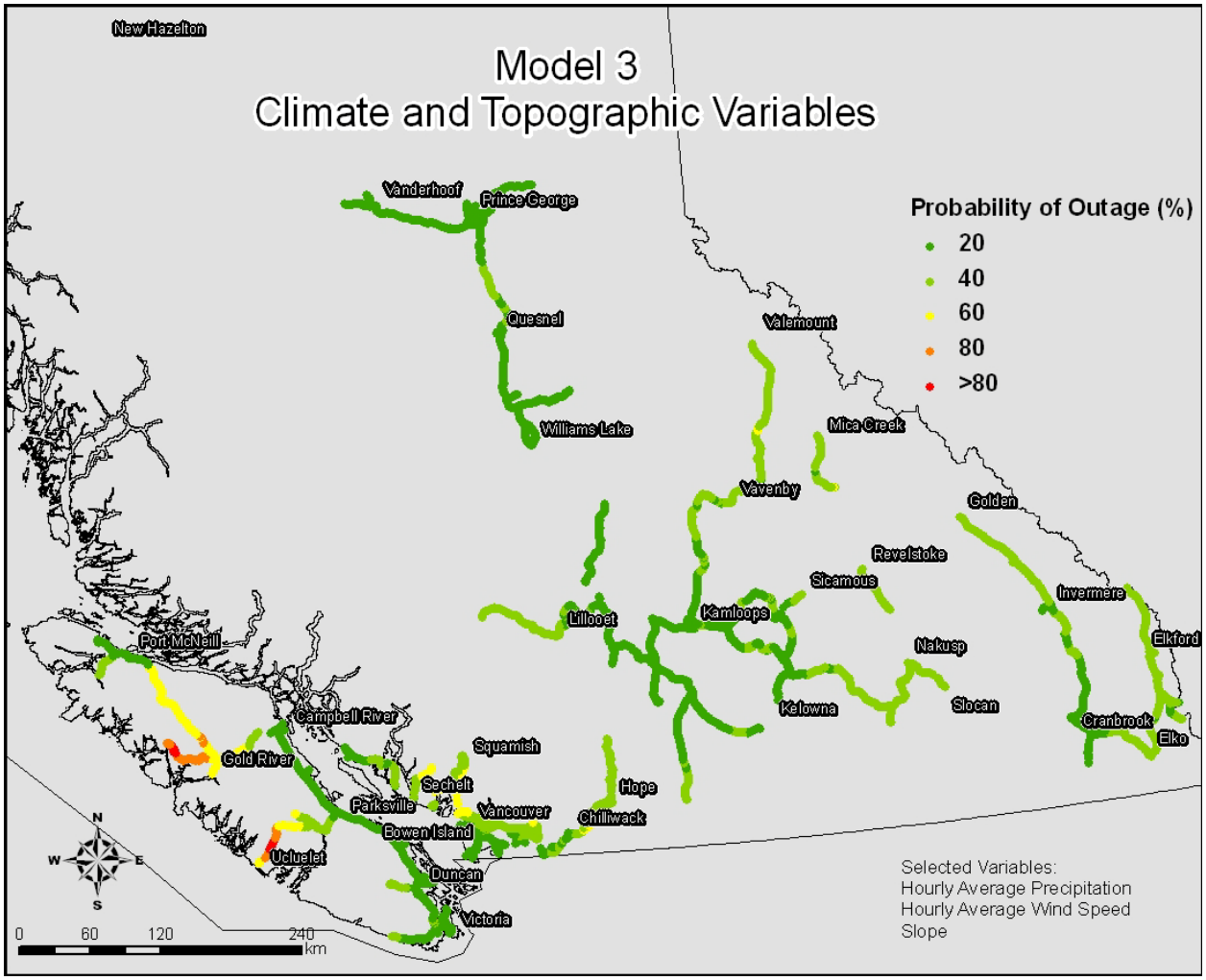


Figure 3.17. The map displays the probability of experiencing an outage according to model 3 using hourly average precipitation, hourly average wind speed and ground slope as predictors. Circuits coloured in dark and light green were predicted to experience less outages than circuits coloured in yellow, orange and red colours.

3.20 Discussion

The main causes of tree-related outages were fallen trees (62%). Flying branches were responsible for 4% of tree-related outages and the remainder were tree-related, but unspecified. Guggenmoos (2009) found that 95% of the tree-related outages experienced by Puget Sound Electricity in Western Washington were caused by fallen trees in the period of 2005 to 2007. The low percentage of branch caused outages is likely a result of vegetation management programs. The BCTC plan aims to replace tall-growing plants with low-growing plants, create incentives

for activities that are ROW compatible (e.g. farming, Christmas tree production), and prevent vegetation growth by pruning and trimming surrounding vegetation (BCTC - Vegetation Management Department 2008).

The winter months experienced more outages than the rest of the year. BC's winter is characterized by large amounts of rain and snow carried by westerly prevailing winds (Watts and Tolland 1983). Winter months also experience stronger winds (above 52km/h) than other months (Environment Canada 2011). High rainfall increases the water content in the soil which results in low soil-root cohesion (Kamimura et al. 2009) and consequently unstable and more wind susceptible trees (Han et al. 2009). During the winter of 2006/07 there were several severe storms in coastal BC. The resulting Winter Storm Report produced by BC Hydro (BC Hydro Corporation 2007), indicates that 1.6 million customers experienced at least one outage from October 2006 to January 2007. Managing ROWs for severe weather events is challenging as these events are localized and with non-defined return period. These winter storms are characterized as catastrophic events and their return periods are usually longer than endemic events (1-3 years return period) but they can be as short as 10 years return period (Navratil 1995).

Lower Mainland and Vancouver Island experienced more outages than the other regions. British Columbia's climate results from the interplay between cool moist air coming in off the Pacific Ocean, and dry cold air from the Arctic. At this latitude, air masses typically move from west to east throughout the year. As Pacific air masses move inland, they rise over the coastal mountains and release precipitation on the western slopes (Mitchell, Read & Hirata 2010). Wind flows more constantly in areas with no topographic obstacles such as water bodies or flat areas (Stathers, Rollerson & Mitchell 1994, Ruel, Pin & Cooper 1998). Naturally areas closer to water bodies would experience stronger winds and potentially more windthrow. Scott and Mitchell (2005)

found that proximity to the coast influenced percentage of windthrow damage. Interior and Central BC circuits were less affected as the eastern slopes of the coastal mountains and the interior plateau are protected by the Cariboo Mountains, Selkirks, Monashees and Rockies produce areas of higher and lower precipitation, and form a barrier to the coldest winter air masses that move south from the Arctic. Lanquaye-Opoku and Mitchell (2005) discovered similar findings. Studying sites in BC interior, West Coast of Vancouver Island, and Queen Charlotte Island they found that damage was greater in latter two.

Transmission ROWs are patrolled annually and hazard/danger tree is dealt with (Wells 2011). As a consequence, tree-related outages are relatively infrequent across the transmission grid (1 outage per 20 km of line, in 18 years). Outages were more concentrated closer to urban areas and this is because the 69 and 138 kV lines are concentrated in these areas and have narrower corridors. However, even when the concentration of transmission lines near urban centres was accounted for, the outage density per km of circuits is higher near cities. According Wells (2011), circuits that are frequently affected typically have a history of high wind exposure, root disease, or environmental conditions (e.g. shallow soils over bedrock) that lead to poor rooting.

Investigating the outage history, years of low occurrence of outages (e.g. 1992, 1997, 2000, 2005, and 2008 from Figure 3.7) were preceded by years of high numbers of outages. Justification for that might be that all the trees were blown down and therefore no trees were left to cause tree-related outages or BCTC maintained the ROWs so intensively and efficiently that the number of outages dropped. The latter one is very unlikely as vegetation management programs are expensive and too time demanding to be done over a single year.

Regarding voltage, the 69 kV circuits experienced more than half of the outages (Table 3.3). Many of these circuits run adjacent to highways, within the highway ROW. For example, the circuit that connects Port Alberni to the Tofino and Uclulet on the west coast of Vancouver

Island runs on the shoulder of Pacific Rim Hwy. Measurements of the highway widths were taken on GoogleEarth© (Google Earth 2011). The road ROW width ranged from 12 to 30 m. The wider width of high voltage ROWs and the distance between phases for the higher voltage systems, makes it less likely that trees will fall across the lines. Trees from within the ROW cause nearly no damage to the transmission lines (Guggenmoos and Sullivan 2007). BCTC ROW's are supposed to have ROW width of at least 10 and up to 300 m – in the case of shared ROW for high voltage lines, however this is not always possible (BCTC - Vegetation Management Department 2008). ROW widths are designed by engineers with electrical safety in mind, rather than vegetation clearances customized to local vegetation communities (Wells 2011).

Climate and topographic variables are typically somewhat correlated. Some variables were strongly correlated to others (e.g. average hourly precipitation and elevation, topex_2k and slope). Strong and moderately correlated variables were kept out of the same model to avoid multi-colinearity (when two variables contribute similarly to a model fit but independently they are not helpful in the model fit). The strong negative correlation between MC2 average hourly wind speed and topographic exposure was expected as areas more exposed to wind such as hilltops generally experience higher wind speeds (Ruel 2000). Lanquaye-Opoku et al. (2005) found low negative correlation between the average hourly wind speed and topex_2k for all the three sites studied in BC. As expected average hourly temperature and elevation were strongly negatively correlated, it is well known that temperature decreases with the increase of elevation (Diaz and Bradley 1997).

There are a few reasons why variables behaved differently when tested for cutblock edges and ROWs. Recently created ROWs are as susceptible to windthrow as new cutblock edges; however most of the ROWs investigated in this research were created a long time ago. This has given time

for the trees to acclimate to the local weather conditions. These ROWs have also undergone many cycles of vegetation maintenance and this should improve the windfirmness of ROW edge trees compared to typical cutblock edge trees. According to Wells (2011) the corridors of the circuits more exposed to winds are more intensively managed, but they are not widened.

In this study, only low voltage transmission lines were examined, which means ROWs were generally located in lower elevations (0 to 1883 m vs. 0 to 4000 m) for the whole province, with lower average hourly precipitation (0 to 0.51 vs. 0 to 0.67 mm/h), lower topographic exposure (-3.45 to 211.72, and -376.86 to 706.48), and lower ground slope steepness (0 to of 48.53 º vs.0 to 89.24º)

The models selected are relatively simple as they carry a maximum of 3 independent variables (Model 3). All the variables selected were not highly correlated avoiding the multicollinearity effect. Consistent with the contingency analyses, outages increase with the increase of precipitation. Moisture content definitely affects tree / branch stability. Luley et al. (2002) found that hourly precipitation provided little increase (R^2 from 0.637 to 0.66) in predicting branch failure using wind gust. Mitchell et al. (2001) found that moist sites were more affected by windthrow then dry sites. Kamimura et al. (2009) found that soil resistance decreases with the increase of water supply. No work has been found regarding the number of outages and precipitation rates but as this research investigates tree related outages, I suspect that tree-related outages increase with the increase in precipitation as it has been found before that outages were more common in the raining season (BC Hydro Corporation 2007).

Unexpectedly, outage decreased with the increase of average hourly wind speed in the models fit and contingency analyses. A number of factors might explain this. Sheltered areas, with old and unstable vegetation where low speed winds are blowing trees over lines could be one explanation for these results. Another situation could be because ROWs that experience high wind speeds

hence, high number of outages have been intensively managed to the point that hazard trees are far from reaching distance to the lines. Also, edge trees routinely exposed to high wind speeds may be acclimated to high wind speeds.

The probability of outage tends to decrease with the increase of elevation. This contradicts with Mitchell and Lanquaye-Opoku (2004) findings studying cutblock windthrow hazard mapping. Different from cutblock edges, ROWs for the 69 and 138 kV lines run in low elevation areas, in the majority of the cases.

A positive coefficient for the variable ground slope was found for both models 2 and 3, and for the contingency analysis. Mitchell and Lanquaye-Opoku (2004) found otherwise. They found a negative relationship between windthrow and ground slope. It is known that hilltops experience significantly different winds than other topographic areas (Ruel, Pin & Cooper 2001). Navratil (1995) stated that wind damage was twice as high in mid and upper slope when compared to lower slope. Further investigation of the effect of slope is warranted.

Models 1 and 3 fit the data well (concordance > 75) model 2 fit the data modestly (concordance = 0.62). Windthrow models performed similarly in other researches. Mitchell et al. (2008) found concordance values ranging from 54 to 70 using stand, cutblock, topography, and climate variables. Scott and Mitchell (2005) found better concordance values (72 to 74) using tree, neighbourhood, and stand attributes.

According to the logistic regression models, climate variables are performing better as predictors for outage locations than topographic variables. On the other hand, topographic variables are more helpful in the process of differentiating lower risk groups from high risk groups (HL chi-square was lowest for the models that included topographic variables). For better understanding of the HL results, the observed and expected values of the lower to high risk groups were plotted

(Figure 3.14). Ideally, for 8 degrees of freedom the chi-square is 15.05, which was not achieved by any of the models. Although all the models covered a good range between lower and higher risk groups as it can be seen on Figure 3.14. However, unlike these earlier studies, it was not possible to split the dataset and test the models on independent data. Also, caution should be exercised when interpreting the models as the Hosmer and Lemeshow Goodness of fit were above the threshold for 10 groups of classes of observed and expected values. Considering the fact that concordance and HL chi-square values were similar to models 1 and 3, Model 1 would be more cost-effective as it has one less variable than model 3.

Xu et al. (2003) and Radmer et al. (2002) used weather data to predict outages caused by trees. Although they advocate that climate variables are useful, they did not conduct spatial analyses. Unlike previous power line outage modelling, my research uses climate datasets produced by numerical weather prediction modelling and topographic data derived from TRIM data. These datasets are available to researchers for free, or at low cost, however they come with some limitations. The models fitted in this research identify areas that are more susceptible to recurrent power outages due to local topographic or climate attributes.

My work used historical outage data. This type of dataset provides information on regions that are more susceptible to outages, the longer the archived period the more consistent the information. There are also limitations in the outage dataset, particularly in the accuracy of the outage locations. The outage dataset covered nearly two decades, but also reflects the particular damaging weather events that occurred during that period. Weather events could occur in long term cycles. Events that occur in a small frequency (e.g. 1-3 years return period) produce less strong winds, been characterized as endemic events, resulting in more uprooted windthrow of the already weakened trees or in trees recently wind-exposed. Events that are more rare tend to produce stronger winds, resulting in stem breakage in localized patches. These events are

characterized as catastrophic events. Since historical outage data was used to fit the model other tools such as field work assessing vegetation conditions regarding ROW clearance should be performed to validate the areas of high risk.

In this modeling approach, outages were modelled as yes/no events along a segment of line. Some areas are more likely to experience multiple power outages during weather events, or experience repeated outages over longer time periods. BC Hydro Winter Storm Report (2007) identified 256 circuits that suffered power outages during the winter of 2006. While these circuits represented only one fifth of the total circuit length in the system, they were responsible for half of the annual customers-hours lost. Simpson and Bossuyt (1996), reviewing the outage history of Brockton in United States revealed that the same 7 circuits were involved in at least 40% of the total Customers Outage Hours from trees during the years of 1990, 1992, and 1994. To further mitigate the risk of future outages in these high outage likelihood locations, a next step would be to create stand-level prescriptions for each ROW segment that would promote stand stability and appropriate line clearances over a series of vegetation management interventions. Identifying areas with higher probability of experiencing weather induced tree-caused power outages would enable targeted prescriptions and reduce cost of maintenance in the long term as well as the increased reliability of power distribution. Fridman and Valinger (1998) emphasized the importance of using climate data in predicting windthrow, but pointed out that many companies rely on employee experience in assessing windthrow hazards. Guesswork is still used by BC Hydro to identify sagging range and wire swung positions (Hooper and Bailey 2004). These assessments could be improved using models such as the ones fit by this research to assess the areas that are more likely to experience tree-related outages when submitted to weather events.

In addition to the spatial datasets used in this study, there are other sources of information that could be used for ROW monitoring and hazard assessments. For example, tree individual crown identification using high resolution remote sensed data and image processing techniques has been used in assessing the danger trees in the vicinity of ROWs in Australia (Li et al. 2008). Hooper (Hooper 2003) used LiDAR (light detection radar) imagery associated with CAD (computer aiding design) software to capture tree heights, compare to line heights and spot danger trees in BC. This proved to be a very good approach as far as identifying the danger trees. The only limitation is the high cost of LiDAR imagery acquisition which limited the author's work to high voltage transmission lines in BC.

BCTC vegetation managers using the outage density analysis and the outage location probability models would be able to assess the sites that are more critical regarding outages occurrences. Vegetation management planers would have another tool to locate areas of high risk and more efficiently use the financial and professional resources to address these ROWs. As good as the models have performed (relatively high concordance values), a more accurate outage history dataset would be of great importance in spatially locating the areas of high risk assuming new and better models could be fit. Including current stand information would also increase the reliability of the models (incentive for the Chapter 4 research) as trees are mainly responsible for outages in low voltage transmission circuits. In other words, accurate spatial location of outages would help to locate the areas more susceptible to tree-related outages.

As future recommendation, a gradual ROW tree-edge management plan to produce wind firm stands where less maintenance (e.g. pruning) would be required. A wind firm ROW edge would not be outage-free but at least endemic event casualties would be less frequent.

3.21 Conclusion

Low voltage circuits with high outage/km density were spatially located. Variables that help to predict the outage locations were identified. The two models developed were able to identify areas more susceptible to experience tree-related outages although the models could not be tested for independency due to insufficient data. This research has demonstrated that it is possible to create models using readily available climate and topographic data to predict the location of power outages caused by fallen trees. Accuracy of the models could be improved with a more comprehensive and accurate spatial dataset with the outage locations. Topographic and climate datasets with higher spatial resolution could further improve the accuracy of the model. Adding vegetation cover should further improve outage models, and this is investigated in the next chapter.

4.0 Predicting electrical distribution circuit outage probabilities across the North Shore using topographic, climate and stand data

4.1 Introduction

In the analysis of transmission outages presented in Chapter 3, I considered climatic and topographic variables as explanatory factors for the occurrence of transmission line outages. The literature review and the previous analysis (see Chapter 2 and 3 respectively) showed that lower voltage transmission systems placed in narrower ROW, experienced more tree related outages than high voltage systems. The distribution grid is similar to the lower voltage transmission lines in terms of ROW, pole, and vegetation characteristics. This is because individual circuits service a relatively small number of customers. Also, because the lines are close to the customers and often run through vegetated areas where public visual perception is of great importance, wide clearances are not acceptable. The distribution grid that supplies the North Shore was chosen for this analysis. The characteristics of the study area are described below in Section 4.4.1.

Distribution circuits are shorter and more densely arranged than transmission lines. Most of distribution circuits are located in urban, suburban or more heavily populated rural areas. Individual circuit lengths range from 0.04 to 613 m. The voltage carried by lines within this grid ranges from 4 to 25 kV in different numbers of phases per circuit. The electricity is distributed in 1, 2, or 3 phase circuits depending on the volume of electricity required.

To facilitate management of the distribution system, BC Hydro supervisors and field crews use proprietary GIS software, the Spatial Asset Management system (SAM) which is loaded on a Toughbook® with built-in GPS. The portable version of SAM is compact, with only the district

database of interest loaded at any point in time. The portable version is updated from a mainframe office version which carries information for the whole distribution grid. SAM includes the asset history such as the vegetation management history, and outage history linked to map layers of the various assets (e.g. poles, transformers). The spatial coordinates of each outage location are recorded during the outage assessment and are included along with other information in an on-line outage database. The outage dataset used in this analysis is a product of SAM.

4.2 Objectives

The main objectives of this chapter were to identify factors that contribute to tree-caused outages and develop statistical models that predict outage locations caused by trees during wind events in the North Shore distribution grid. Along with outage data, topographic, climatic, and stand data were used in this analysis.

My research questions were as follows:

1) are tree-related outages localized in clustered patterns, or are they spread randomly throughout the study area;
2) what do locations with higher concentrations of outages have in common in terms of topographic, and climatic conditions;
3) can topographic, and climatic variables be combined to predict the locations of tree-related outages?

4.3 Hypotheses

The main hypothesis is that topographic, climate, and stand variables are useful predictors of the location of the outages caused by trees. A secondary hypothesis is that outages are clustered within the distribution grid. In the case of clustered distribution of outages, are they clustered in areas with a higher predicted probability of outages?

4.4 Material and methods

4.4.1 Study area

The distribution grid is divided into 2 regions (Interior and Lower Mainland/Vancouver Island), covering 8 areas: Metro Vancouver, Fraser Valley, North Vancouver Island, South Vancouver Island, Thompson/Shuswap, Okanagan/Kootenay, Central Interior, and North East/West Interior (BC Hydro Corporation 2008). While there is less variability in climate and topographic characteristics within this region than in the province as a whole, this is still heterogeneous terrain with gradients in rainfall. Land cover also varies within this area, ranging from urban to rural to densely forested areas.

The area under study is the North Shore District (NS District) of the Lower Mainland Region, and covers from Bowen Island to Lions Bay, across the North Shore of English Bay and Burrard Inlet to the end of Indian Arm in North Vancouver (Figure 4.1). The NS District was selected for study because it is a heavily populated and well forested area with great terrain complexity (steep slopes, valleys, mountains, rivers, and shores), features that affect windthrow rates, and presumably the rate of tree-related outages.

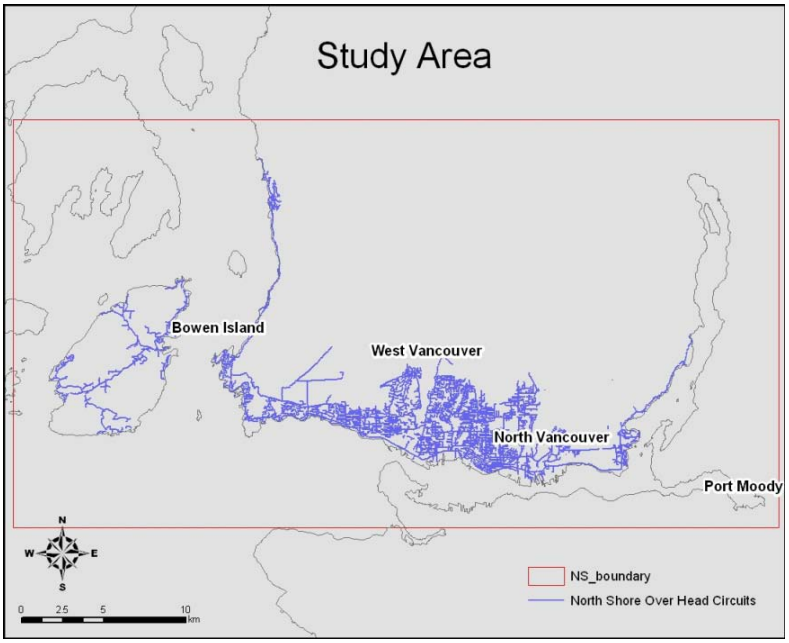


Figure 4.1. The study area is limited within the limits of the red border polygon. The blue lines represent the distribution grid.

4.5 Spatial datasets

4.5.1 Assets dataset

While the SAM software is an operational system and is useful for investigating specific outages and maintenance histories, it is not compatible with other GIS systems or layers. BC Hydro therefore exported spatial datasets with information about circuit voltage, number of phases, substations, poles, street, and communities to shapefiles. Shapefiles are in the Universal Transversal Mercator (UTM) geographic coordinate system and the datum used was NAD 83. Information about object id, length, voltage, customers affected were included as attributes.

4.5.2 Outages dataset

The outage categories: fallen trees, fallen branches and grow-ins were explained in Chapters 2 and 3. The North Shore dataset also includes adverse weather as a direct cause of power outages. Outage causes during adverse weather include lightning, line slap, and iced conductors among

others. Outages caused by fallen trees/branches during severe weather events are listed under the separate category of tree-related outages. The distribution circuit outage dataset was provided by BC Hydro in shapefile format. This dataset contains information about the circuit id, cause of outage (adverse weather, fallen tree, fallen branch, and grow-in branches), outage location, time and date of outage, voltage of the circuit affected, type of weather at the time of the outage, and number of customers affected. Each record has information for an individual outage. The outage records were collated by BC Hydro in SAM. The data covered the period of October 12, 2005 to August 15, 2009 and included a total of 701 outages caused by fallen trees, each of which had known coordinates accurate to within a few meters. Only this category of outages (fallen trees) was used for analysis and modelling.

4.5.3 Control point dataset

The purpose of the control point dataset was to represent conditions across the whole North Shore distribution network to use for comparison with outage locations, and for subsequent model fitting. The control point dataset was created using a set of tools and operations in ArcMap®, as follows. From the circuit shapefile (line feature shapefiles where one line represents one circuit) the lines representing the circuits were all merged together using the Merge tool. This operation was required because evenly spaced points cannot be created in separate objects (in these case circuits). With this single merged circuit selected, the Divide tool was used to create control points. This 100 m distance was used because it fell within the range of spatial resolution of the raster and vector variables that were to be used as predictors. As the circuit information was needed for the subsequent analysis, all of the information in the original circuits' layer was extracted to the control points.

4.5.4 Stand variables

Oliver et al. (1996) define a stand as a spatially continuous group of trees having similar structures and growing under similar soil and climate conditions. The stand dataset used in this study was the Vegetation Resources Inventory (VRI), obtained from the Land and Resource Data Warehouse. The stand attributes are defined in the VRI Relational Data Dictionary (2007). The variables used in this study were stand age, height, site index, and crown closure. Age is the average age, weighed by basal area, of the dominant, co-dominant and high intermediate trees for the leading and second species of each tree layer identified. In the VRI dataset, the stand height is the average tree height, weighted by basal area of the dominant, co-dominant, and high intermediate trees for the leading and second species of each tree layer. Site index is an estimate of site productivity for tree growth (height in meters at breast height at the age of 50 years for a given species). Crown closure is the percentage of ground area covered by the vertically projected crowns of the tree cover for each tree layer within the polygon and provides an estimate of the stocking.

4.5.5 Topographic variables

The topographic variables used in this research (elevation, topex_2k, and ground slope) are from the TRIM derived dataset described in Chapter 3.

4.5.6 Climate variables

The climate data used in this analysis are from the MC2 and BC Hydro numerical weather prediction model datasets described in Chapter 3 and include the hourly average wind speed (km/h), hourly average temperature (ºC), hourly average precipitation (mm/h), top 5 events wind speed (km/h) at a 4 km spatial resolution and 1 km spatial resolution for BC Hydro annual average wind speed (m/s).

4.6 Assumptions and limitations

The limitations concerning the topographic and climate data are the same as in Chapter 3. Since the study area is much smaller, the relatively low spatial resolution of the climate data becomes more limiting in representing the true climatic variability in this geographically and topographically varied district.

It is assumed that VRI data represents the areas dominated by native forest vegetation. While the NS District is heavily forested, the tree canopy is made up of native and non-native species in the more populated areas. The stand information was missing for some of the records. These records were excluded from the modelling process. Control points and outage records were verified regarding information carried about the extracted variables. Records with invalid information (e.g. wrong topex data) were fixed or excluded (in case of inaccurate data) from the modeled dataset.

According to BC Hydro (Wells 2011), line crews are responsible for filling the reports and often they used adverse weather and tree caused outage codes interchangeably. Therefore, the number of tree related outages could be inflated or deflated. BCHydro estimates that 40% of the outages are caused by trees across the provincial distribution grid.

4.7 Analysis

Exploratory analysis of the outage dataset was performed prior to spatial and statistical analysis. The total number of outages and the number of customers affected were examined for each type of cause of outage.

The outage locations and the control points datasets were merged in one single dataset. Prior to the merger, a new variable “STATUS” was created in each dataset where value of 1 was assigned to the outage records and value of 0 to the control point records. Variables values such

as elevation, topographic exposure, slope, hourly average data (wind speed, temperature, and precipitation), BC Hydro annual average wind speed, top 5 events wind speed, and stand variables were extracted to each of the points in the merged dataset.

4.8 Statistical analysis

The statistical analysis and model selection performed in this chapter follows the same procedures as in Chapter 3. The main difference is the size of the final dataset. The final dataset included 581 outage points and 1413 control points for a total of 1994 records. The number of outage records was reduced from the original 701 prior to the analysis because some locations did not have stand data.

4.9 Outage density

Outage density mapping was used to identify the areas that experienced more outages per given length of electrical circuit. This was done using the Point Density tool. First, a raster of the outage cluster was created for a cell size of 100 m with a search radius of 300 m. This process scans the buffer area of 300m radius and assigns the number of outages within it to the center pixel. A similar process is performed to map the circuit cluster but instead of number of circuits it sums the length of the circuits within the buffered area. The tool for this operation is called Line Density. The final process uses the Divide tool. The outage cluster raster is divided by the circuit cluster raster to produce the outage density raster (outage per length of circuit). The final product is a raster file that shows the areas that are most affected by outages considering the length of circuits in that area. The process is described in Appendix B. with the exception of the Raster to Polygon step for point and lines files.

4.10 Results

4.10.1 Outage causes

Adverse weather caused almost half of the total outages and accounted for more than half of the number of customers affected by outages during the 5 year period (2005 to 2009; Table 4.1). Branches growing into the lines (Tree grow-ins) accounted for only 4% of the total outages. Trees falling and tree branches accounted for 51 % of the total outages.

Table 4.1. Causes of outages (data collection period 12th of October of 2005 to 15th of August of 2009)

	Outages		Circuits Affected		Customers Affected	
Causes	#	%	#	%	#	%
Tree grow-ins	99	4	28	0	1,074	0
Tree falling	701	27	279	2	61,757	26
Tree branches	631	24	170	1	38,212	16
Adverse Weather	1,208	46	389	2	139,364	58

No. of Outages=2639, No. of Circuits Affected=866, No. of Customers=240,407.

4.10.2 Outage trends throughout the year

There was a strong seasonal pattern in outages caused by fallen trees (Figure 4.2). Of the 701 outages in this category, 80% occurred from November to February, with the highest peak in November (30% of total) and few outages during the spring and summer months. The year 2006 had the greatest number of outages. The number of outages decreased in each of the subsequent years (Figure 4.3).

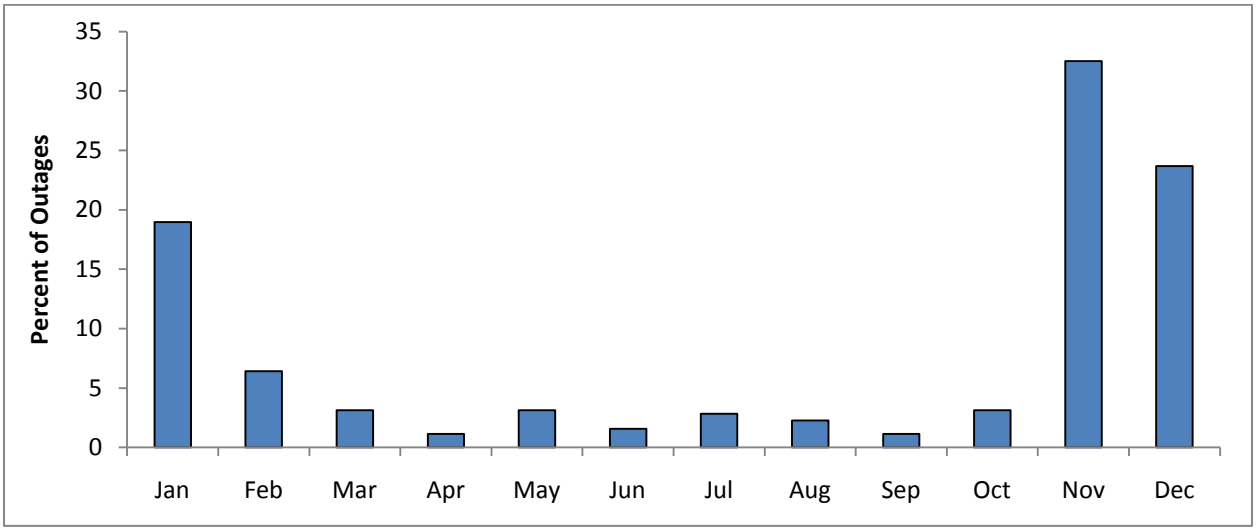


Figure 4.2. Outages distribution by month (data collected from 12th of October of 2005 to 15th of August 2009)

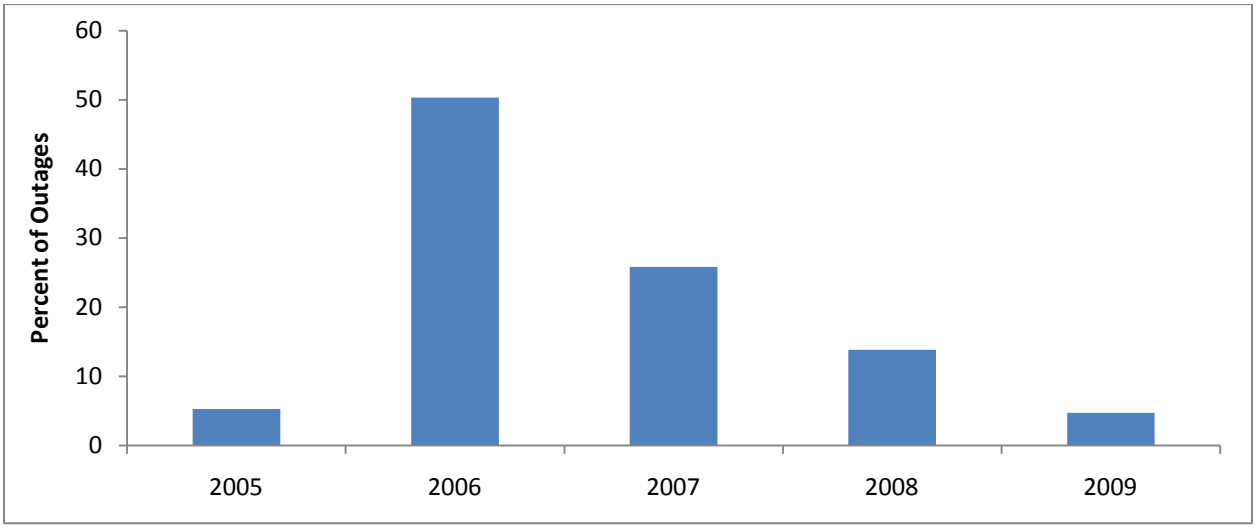


Figure 4.3. Outages distribution by year (12th of October of 2005 to 15th of August 2009). The 2006 experienced half of the outages from the outage dataset.

4.10.3 Outages by number of phases

Circuits with 1 and 3 phases (number of conductors per circuit required to supply electricity to region) were the most common circuit configurations within the distribution grid and 1-phase circuits experienced more outages (Figure 4.5). Over 50% of the outages occurred in 2006 (353). From the complete year period, 2008 was the last affected year with 97 outages among 1 and 3

phase circuits. The 3-phase circuits carry higher voltage which explains their distribution with long circuits reaching areas where the 1-phase circuits supplies the customers in general.

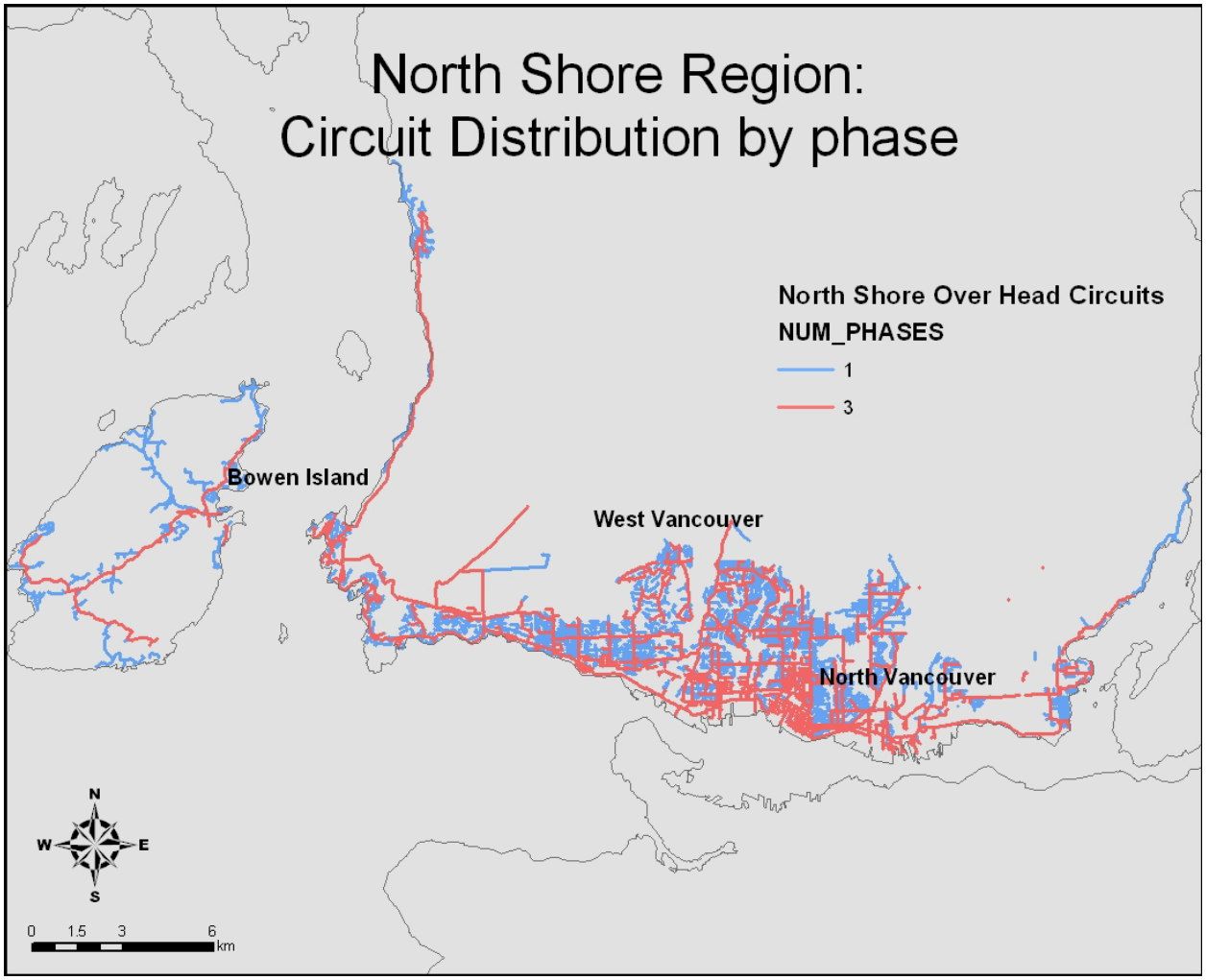


Figure 4.4. North Shore Circuits Distribution by number of phase per circuit. Three-phase circuits carried higher voltage distributing electricity to central areas which are then supplied by the 1-phase circuits, hence the distribution pattern.

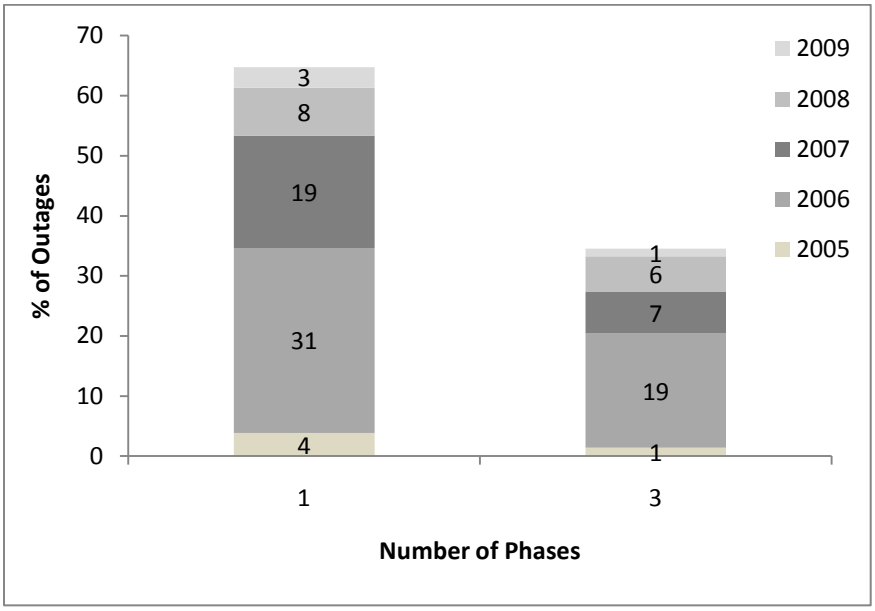


Figure 4.5. Percentage of outages by phase and year

No. of outages = 701. No. of circuits=16656

4.10.4 Outages per voltage

Each circuit voltage category has a particular spatial distribution. The 12.5 kV circuits have the greatest length of lines and the highest number of outages (Table 4.2). However when expressed as outages per km of line, the 4 and 12.5 kV lines experienced the same outage density per km of line (25). The 25 kV circuits have fewer circuits and experienced fewer outages than the 4 and 12.5 kV circuits. In terms of customers, 25 kV system supplies almost 200 customers per km of line, and consequently, more customers are affected during outages on 25 kV circuits.

Table 4.2. Fallen tree outage density per voltage circuit.

Circuits				Outages			Customers
Voltage	Length (km)	% affected	# affected	#	%	outage/km	customer/km
4	72	0.8	16 (2,004)[a]	54	8	25	16
12.5	511	1.2	166 (13,288)[a]	491	70	25	87
25	70	7.1	97 (1,364)[a]	156	22	18	198

[a] Total number of circuits, [b] Total number of customers affected per voltage

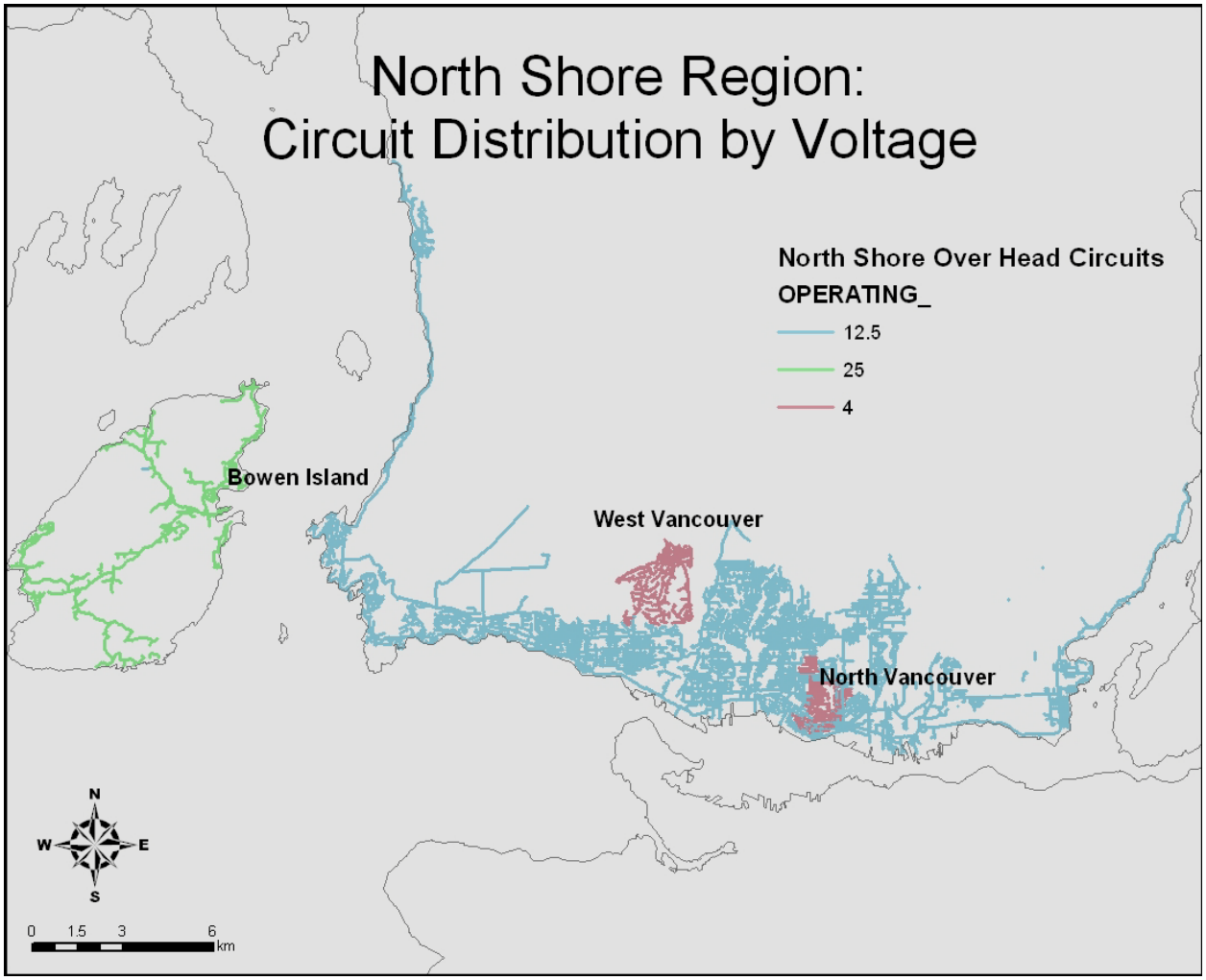


Figure 4.6. NS circuit distribution by voltage. The 4 kV lines are clustered in two patches, the 25 kV line covers Bowen Island, and the 12.5 kV lines connect the remaining areas in the study site.

4.10.5 Outage density

Outages were distributed in clusters (shades of blue patches) across the NS district (Figure 4.7 to Figure 4.8). Outage density clusters were present in Horseshoe, Bowen Island, Lions Bay, Capilano, Lynn Valley, and North Woodlands located on the west side of the Indian Arm. Many of these clusters were in low lying areas close to the ocean, but other clusters were well inland, and at higher elevations.

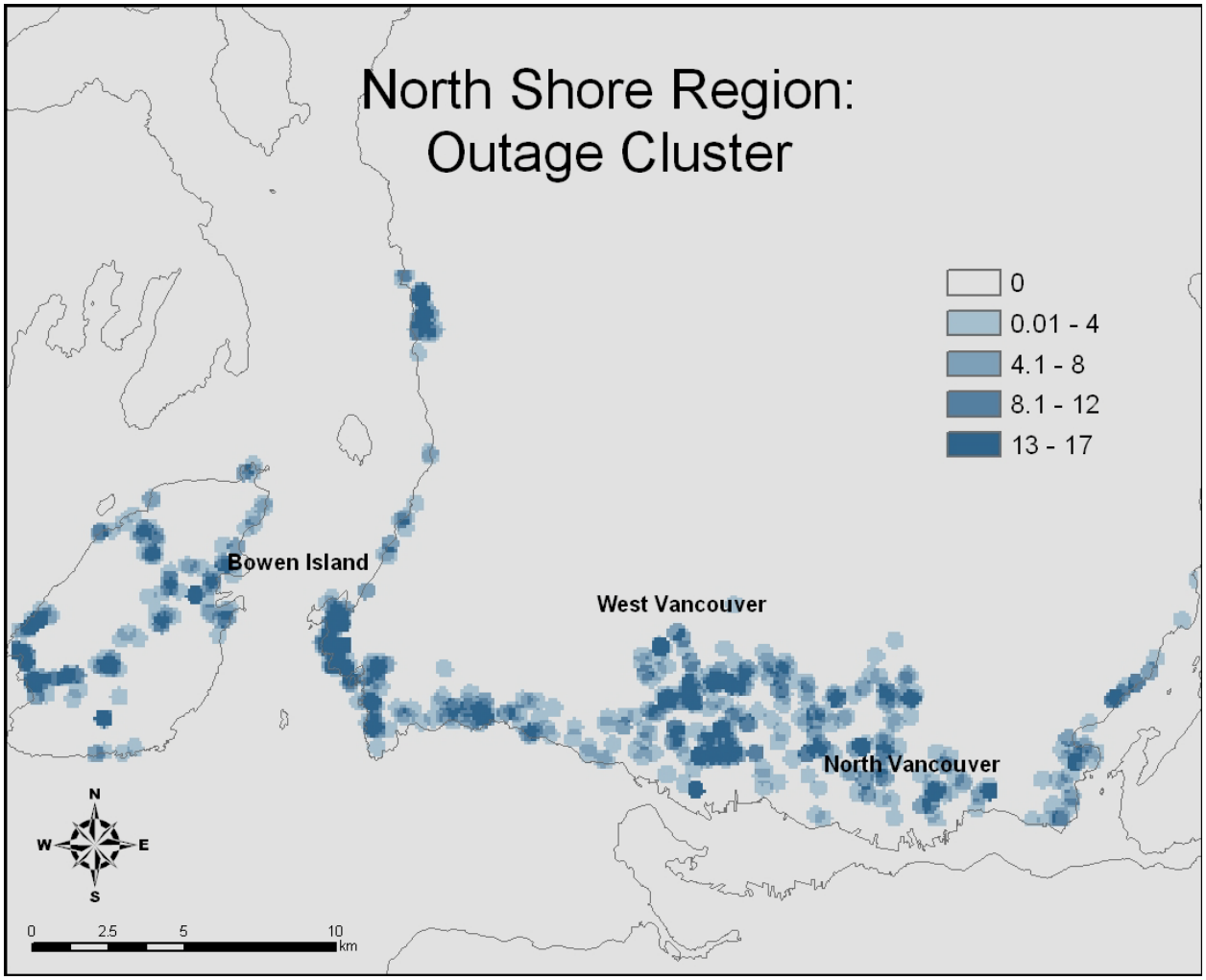


Figure 4.7. Cluster of Outages (in km) within a 300 m radius (cell size of 100 m). Values reflect the number of outages within a 300 m radius assign to a 100 m center cell. The final measurement was converted to outages per km and these were classified in 5 classes of equal interval covering the whole range from 0 to 17 outages / km.

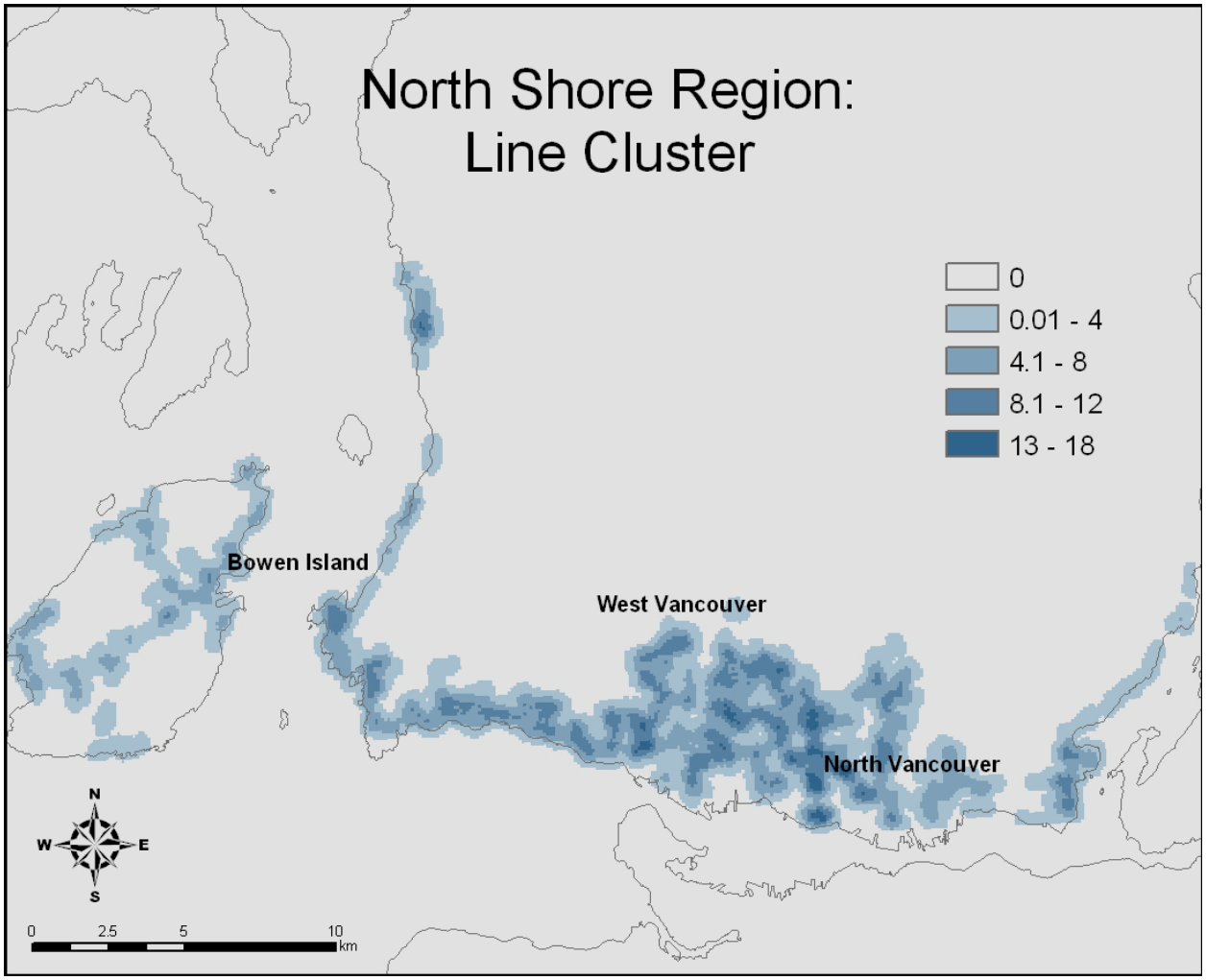


Figure 4.8. Cluster of lines (in km) within a 300 m radius (cell size of 100m). Values reflect the length of lines within a 300m radius assign to a 100 m center cell. The final measurement was converted to lines per km and these were classified in 5 classes of equal interval covering the whole range from 0 to 17 outages / km.

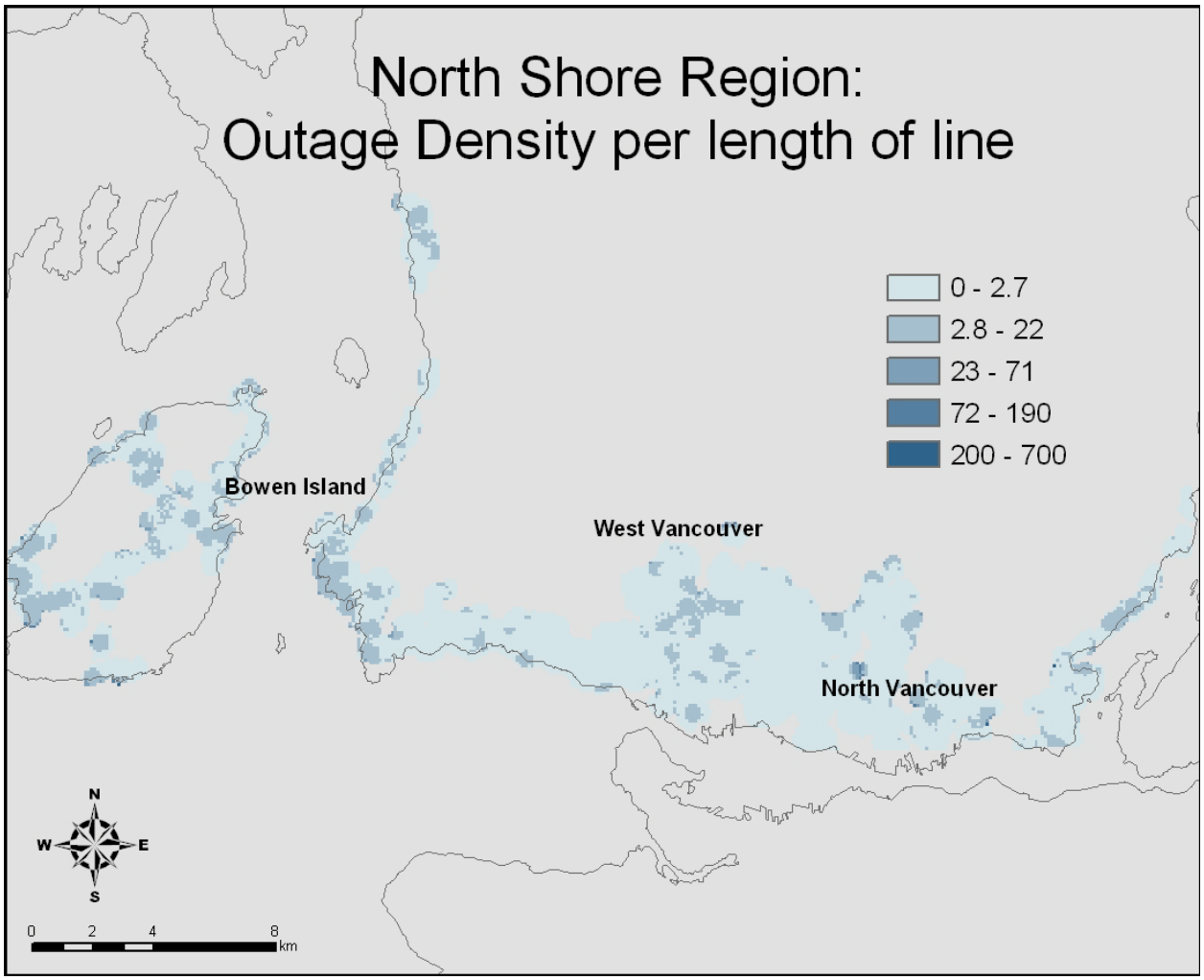


Figure 4.9. Tree-fall caused outage density across the North Shore Region. Shades of blue indicate the local density of outages per length of circuit (outage/km). Areas in white detail are areas with low outage/km density or no outages (e.g. circuits running towards north, west of West Vancouver). Darker tones of blue indicate areas with high density of outages/km.

4.11 Statistical results

The dataset used for model fitting, contingency tables, and correlation between independent variables had 581 outage records and 1413 control points (total 1994). Potential predictors included stand, topographic and climate variables (Table 4.3). On average, the locations with outages did not vary in topographic, climate, and stand attributes from the control locations.

However, areas with higher densities of outages per length of line have slightly taller and older stands with higher crown closure, and are slightly more sheltered than the control locations.

Table 4.3. Summary of key variables for outage locations, control locations and areas with high outage densities per km of circuit.

Variables	Label	Outage			Control Points			High Density Areas		
		Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Stand Age	AGE_1	67.5	8	140	64	5	175	71	5	175
Stand Height (m)	HEIGHT_1	27	3	45	26	4	44	29	3	45
Crown Closure (%)	CR_CLOSURE	22.6	1	85	18.52	2	80	30.5	1	80
Site Index	SITE_INDEX	25	13	38	25	13	36	26	13	38
Average Hourly Precipitation (mm/hr)	APCP	0.2	0.11	0.38	0.16	0.11	0.24	0.2	0.11	0.38
Average Hourly Wind Speed (km/h)	MWS_ANNUAL	5.4	1.58	13.08	5.42	1.58	13.08	5.5	1.58	13.08
Average Hourly Temperature (ºC)	AVGT	10.9	7.16	12.02	10.87	8.00	12.02	10.9	7.16	12.02
Top 5 Events Windspeed (km/h)	WS_5Y	6.1	2.70	15.48	6.12	2.70	15.48	6.3	2.7	15.48
BC Hydro Mean Windspeed (m/s)	BCH_WS	3.1	2.19	4.31	3.08	2.19	4.20	3.22	2.19	4.31
Topographic Exposure	TOPEX_2K	43	-14	164	37	0	152	50	-14	164
Elevation (m)	ELEVATION	103	5	840	119	2	397	93	2	840
Slope (º)	SLOPE	9	0	39	8	0	39	10	0	39

4.11.1 Correlation between independent variables

Prior to model fitting, Pearson correlations among potential predictor variables were examined. As expected, there were some significant correlations (Table 4.4). Topographic exposure decreased (index increased) with increasing ground slope. Average hourly precipitation was negatively correlated with the various measures of wind speed and temperature, and increased with elevation. Wind speed and temperature decreased with elevation. The two different estimates of average hourly wind speed (MC2 and BC Hydro) were only weakly correlated. Stand height increased with stand age. Crown closure decreased with topographic exposure.

Table 4.4. Pearson correlations between potential predictor variables, correlation coefficients

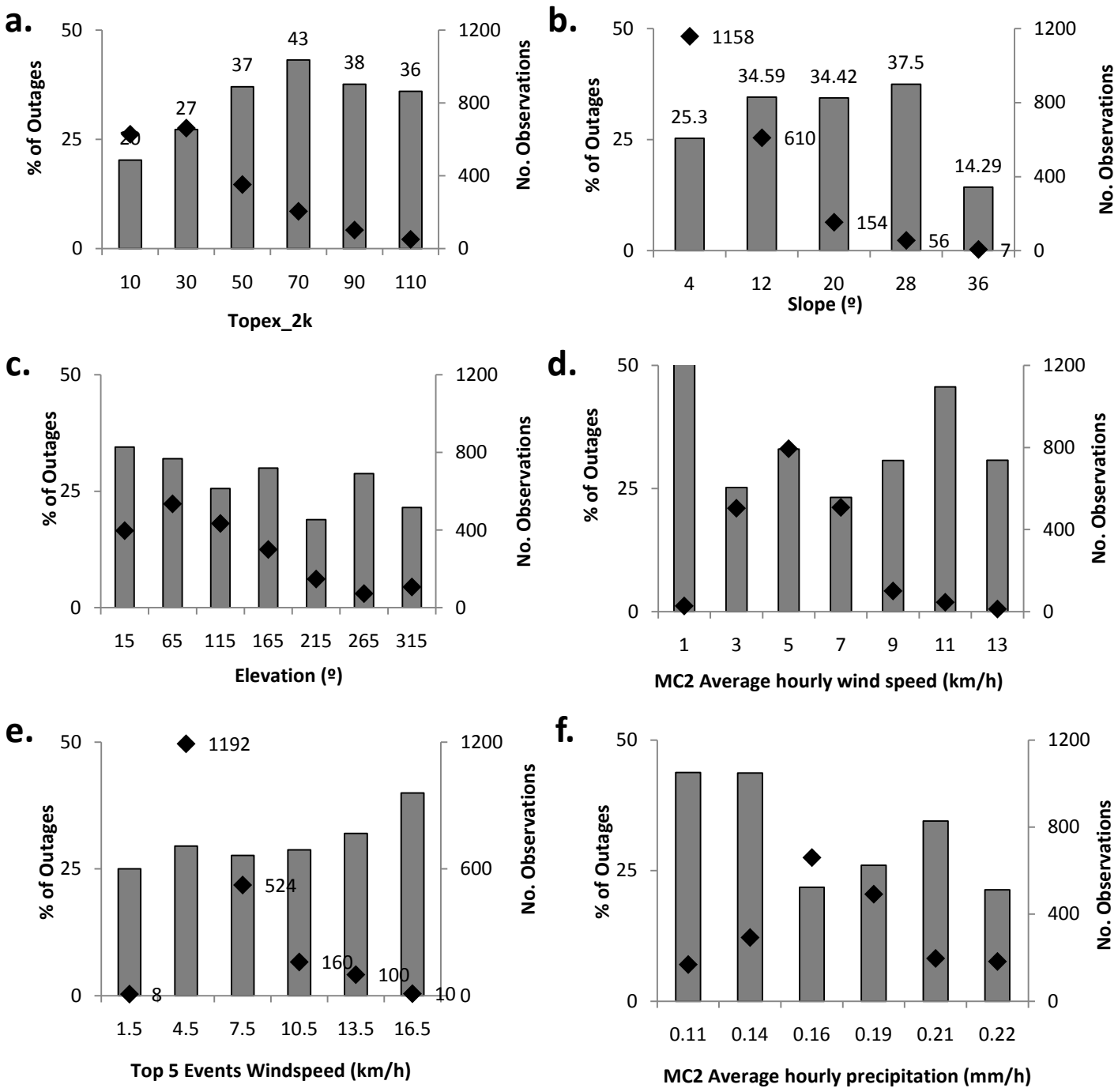
	AGE	HEIGHT	CR_CLOSURE	SITE_INDEX	APCP	MWS_ANNUAL	AVGT	WS_5Y	BCH_WS	TOPEX_2K	ELEVATION
HEIGHT	**0.78**										
CR_CLOSURE	Ns	0.21									
SITE_INDEX	-0.29	0.28	0.31								
APCP	-0.28	-0.30	-0.15	-0.10							
MWS_ANNUAL	0.20	0.19	0.05	ns	**-0.72**						
AVGT	0.22	0.20	-0.11	ns	**-0.68**	**0.71**					
WS_5Y	0.13	0.14	0.13	ns	**-0.60**	**0.90**	0.53				
BCH_WS	0.12	0.21	0.29	0.26	-0.46	0.19	ns	0.09			
TOPEX_2K	0.19	0.23	0.45	0.16	-0.21	ns	ns	0.10	0.32		
ELEVATION	-0.23	-0.21	ns	ns	0.59	-0.50	**-0.62**	-0.42	0.23	-0.07	
SLOPE	Ns	0.06	0.38	0.17	ns	ns	-0.07	0.07	0.19	**0.67**	0.16

Results are given as 'ns' where the correlation is non-significant correlation (*P>0.05*) Good to strong correlations are bolded.

AGE = stand age from the VRI, HEIGHT = stand height from the VRI, CR_CLOSURE = percentage of crown closure from the VRI, SITE_INDEX = site index from the VRI, APCP = average hourly precipitation from MC2 model, MWS_ANNUAL = average hourly wind speed from MC2 model, AVGT = average hourly temperature from MC2 model, WS_5Y = Top 5 events wind speed from MC2, BCH_WS = BC Hydro annual average wind speed, Topex_2k = Topographic exposure.

4.11.2 Relationship between outage frequency and predictor variables

The proportion of all points (outage and control) with outages for a given class of a predictor variable is referred to as the outage frequency. There was a general increase of outage frequency with the increasing stand height, stand age (no trend was found between site index and the outage frequency) topex_2k, and top 5 events wind speed (Figure 4.10). Outage frequency decreased with average hourly precipitation. There was no trend in outage frequency with average hourly wind speed, ground slope, or crown closure.


a.
% of Outages
No. Observations
Topex_2k
10 30 50 70 90 110
20 27 37 43 38 36
b.
Slope (º)
4 12 20 28 36
25.3 34.59 34.42 37.5 14.29
1158 610 154 56 7
c.
Elevation (º)
15 65 115 165 215 265 315
d.
MC2 Average hourly wind speed (km/h)
1 3 5 7 9 11 13
e.
Top 5 Events Windspeed (km/h)
1.5 4.5 7.5 10.5 13.5 16.5
1192 524 160 100 8 10 0
f.
MC2 Average hourly precipitation (mm/h)
0.11 0.14 0.16 0.19 0.21 0.22

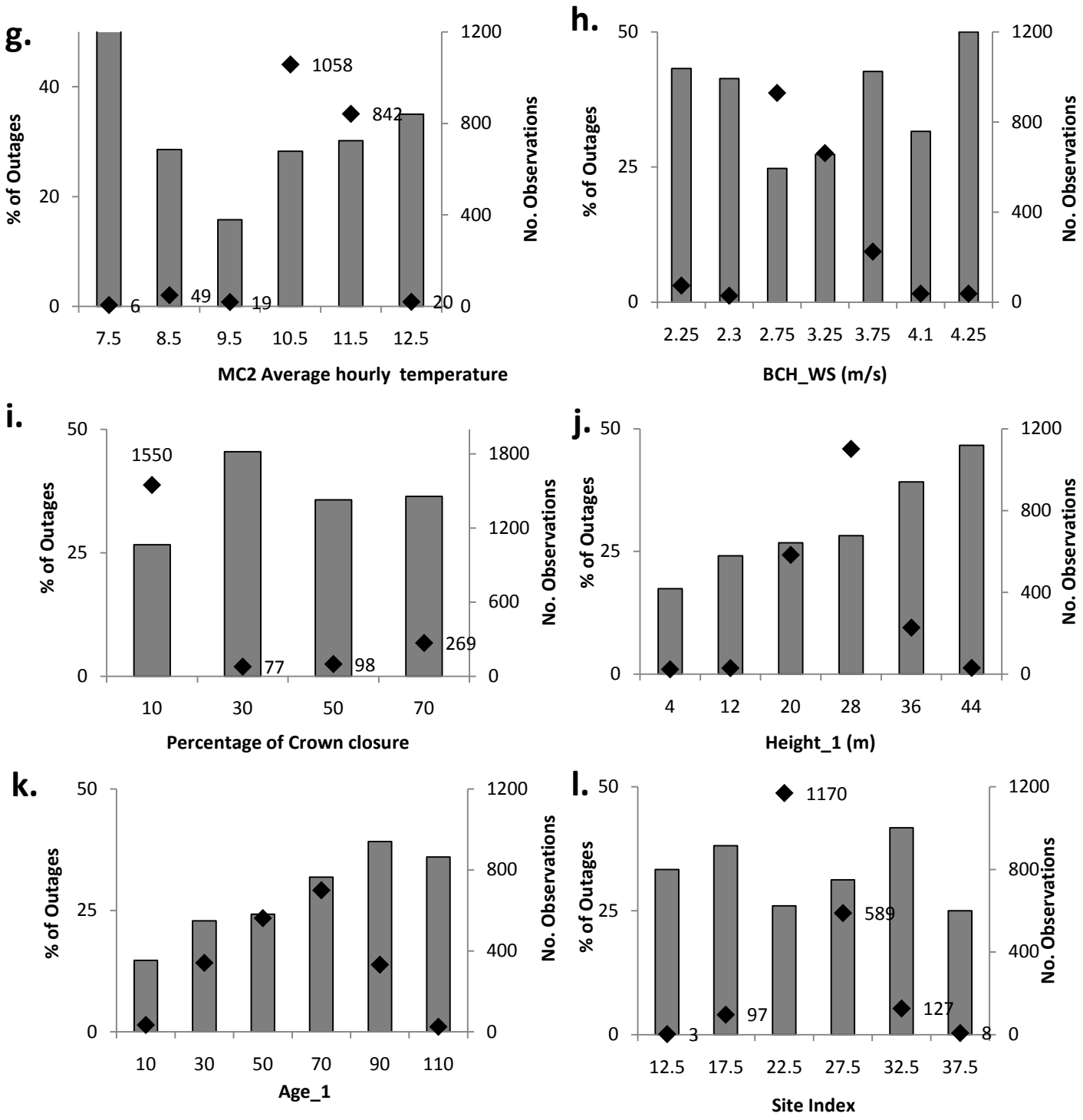


Figure 4.10. Bar graphs showing the frequency of outages for the climate and topographic variables. Diamonds are the total number of observations (control points and outages), the bars are the percentage of observations that are outage points for each class of each

4.12 Models

Seven models were fitted using stand, climate, and topographic variables using logistic regression (Table 4.5). The first three analyses were produced using topographic, climate, and stand variables separately, producing Model 1, Model 2, and Model 3 respectively. Models 4, 5, and 6 were produced using combinations of topographic and stand, topographic and climate, and stand and climate variables respectively. The last model used information from all of the datasets (topographic, climate, and stand) producing Model 7 as a result. The topographic variables-only model selected elevation and topex_2k as predictors. The climate variables-only model selected BCH_WS average wind speed and hourly average precipitation. The stand variables-only model selected stand height and stand cr_closure. The topographic-stand variable model selected elevation, topex_2k, and stand height. The topographic-climate variables model selected elevation, topex_2k, BCH_WS average wind speed, and top 5 events wind speed. The climate-stand variables model selected stand age_1, stand cr_closure, and hourly average wind speed. The topographic-climate-stand variable model selected topex_2k, height_1, and top 5 events wind speed as predictors.

Across all the models, outage probability increases with the increase of topex_2k, stand age_1, stand height_1, stand cr_closure, and BCH_WS average wind speed. Outage probability also increases with the decrease of elevation, hourly average wind speed, top 5 events wind speed, and hourly average precipitation.

The models generally had a poor to moderate fit (a c-value of 0.5 is no better than chance, good models have c-values above 0.7). Models 4, 5, 7, and 1 were better (c-values of 0.63, 0.62, 0.62, and 0.62 respectively) while models 2, 3, and 6 had the worst fit (c-values of 0.55, 0.60, and 0.61 respectively). The HL Chi-square test results indicate model goodness-of-fit and also how well models were able to distinguish between low and high probability classes. For 10 classes (degree

of freedom of 8), the critical chi-square value is 15.507 (p=0.05) (Tabachnick and Fidell 2007). Model 5 had the best fit (15.09) and model 7 had the second best fit (25.08) and both of these models gave reasonable discrimination between high and low outage probability classes (Figure 4.11). Models 2, 3 and 6 poorly differentiated high from low probability classes. The H-L plots for models 1, 2, 3, 4, and 6 are in Figure C.2 from Appendix C.

Table 4.5. Summary of the models fit using logistic regression and the three classes of predictors. Models in bold were selected as they presented better combination of c-value and HL Chi-square test.

Variables	Model1	Model 2	Model 3	Model 4	**Model 5**	Model 6	**Model 7**
	Topographic	Climatic	Stand	Topographic Stand	**Topographic Climatic**	Climatic Stand	**Topographic Climatic Stand**
Intercept	-1.0932	-0.0031	-2.2431	-1.995	**-1.567**	-1.8253	**-1.4127**
ELEVATION	-0.00218	-	-	-0.00188	**-0.00325**	-	**-**
TOPEX_2K	0.0118	-	-	0.0101	**0.0104**	-	**0.00968**
AGE_1	-	-	-	-	**-**	0.0142	**-**
HEIGHT_1	-	-	0.0459	0.035	**-**	-	**0.0331**
CR_CLOSURE	-	-	0.00669	-	**-**	0.00902	**-**
BCH_WS	-	0.1136	-	-	**0.3416**	-	**-**
MWS_ANNUAL	-	-	-	-	**-**	-0.03	**-**
WS_5Y	-	-	-	-	**-0.0669**	-	
APCP	-	-7.3601	-	-	**-**	-	**-4.3234**
c-value	0.62	0.55	0.60	0.63	**0.62**	0.61	**0.62**
concordance	61.6	54.3	58.9	62.7	**61.9**	60.3	**62**
discordant	37.6	43.8	37.5	36.5	**37.4**	38.1	**37**
HL Chi-Square	34.8303	77.2235	52.0974	31.841	**15.0906**	41.6134	**25.0837**

n=1994, number of iterations = 110952. HL chi-square for 8 degrees of freedom is 15.5073 (p=0.05) (Tabachnick, Fidell 2007)**.**

The Logistic Regression produces the logit, which is transformed in to probability values for each specific location using the equation:

Figure 4.11 shows the observed (y-axis) and expected (x-axis) low and high risk probabilities groups plotted against each other. The solid line indicates the 1:1 relationship which provides an idea how a perfect model would perform where the observed and expected groups would have identical values. The probability groups for Model 5 are more uniformly distributed along the 1:1

line when compared to Model 7. Model 5 also covers a wider range of values between the low and high risk probabilities groups.

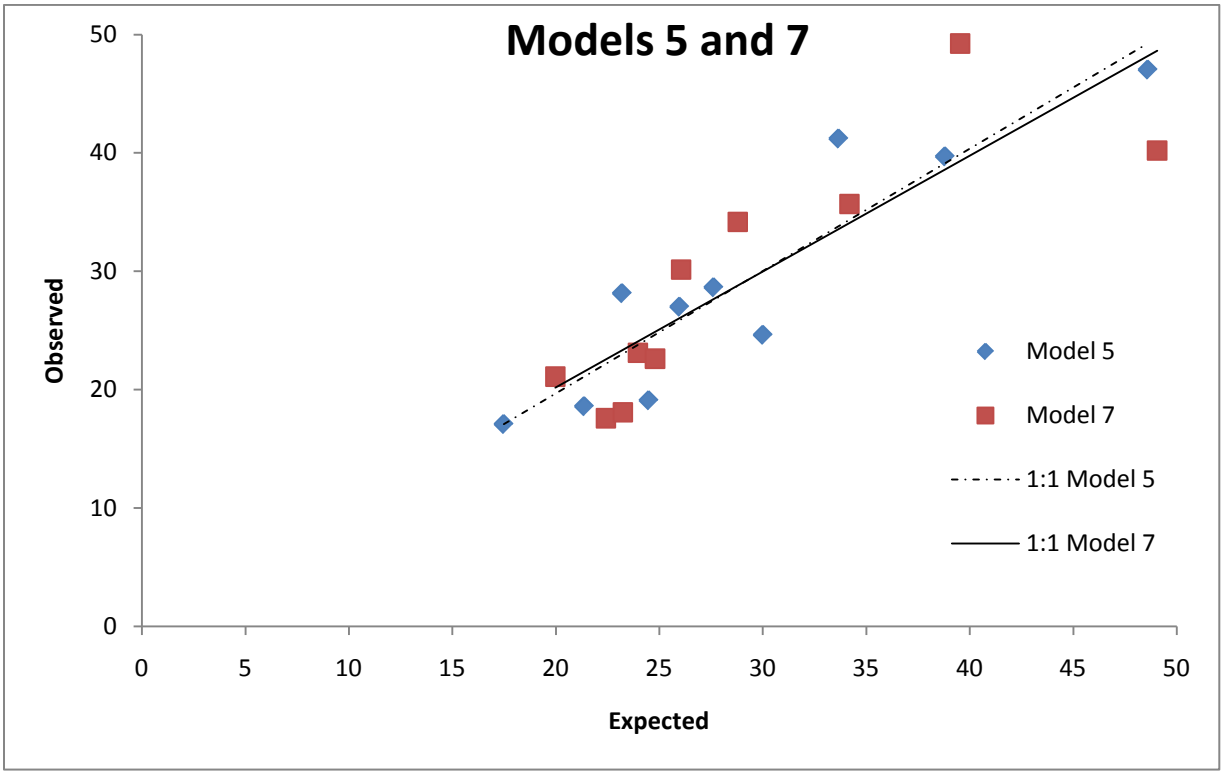


Figure 4.11. Hosmer and Lemeshow Goodness of Fit plot. Models 5 and 7 probability groups were plotted (observed vs. expected) to show the range of values covered by the models as well as the differentiating capacity between low and high probability classes of each model.

4.13 Map of the selected models

The models 5 and 7 were selected to be mapped based on their c-values and HL chi-square test results. Both of these models predicted high probability of outages for the circuits located in Bowen Island, Horseshoe Bay, Lions Bay, and Indian Arm (Figure 4.12 and Figure 4.13). Model 5 predicted lower probability of outage for the circuits located in the Cypress Mountain, Capilano, and Lower Lynn Valley areas. Model 7 predicted similar low probability of outages but in smaller patches within the same areas.

The outage location probability models correctly predicted high probability of outages for part of the areas classified as having high outage densities (outages per km of line).

From a total of 5631 records, 247 records did not have outage per length of line information. Using a threshold of 1.4 outage/km (average value of outage in relation of length of line) a total of 1873 (35 % of the total number of records) records were classified as being above average in terms of outage per length of line (Table 4.6). Model 5 and 7 classified 23 and 24 % of the 1873 records as high probability outage location.

Table 4.6. This table compares predictability models'performance to outage in relation of length of line analysis

Outage Model and Outage Density Analysis		
	Number of records	Percent of records
Records w/ out/km info	5384	100.00
Threshold above 1.4 outage/km	1873	34.79
Model 5	431	23.01
Model 7	452	24.13

Number of records with high probability of are calculated as percentage of high outage/density.

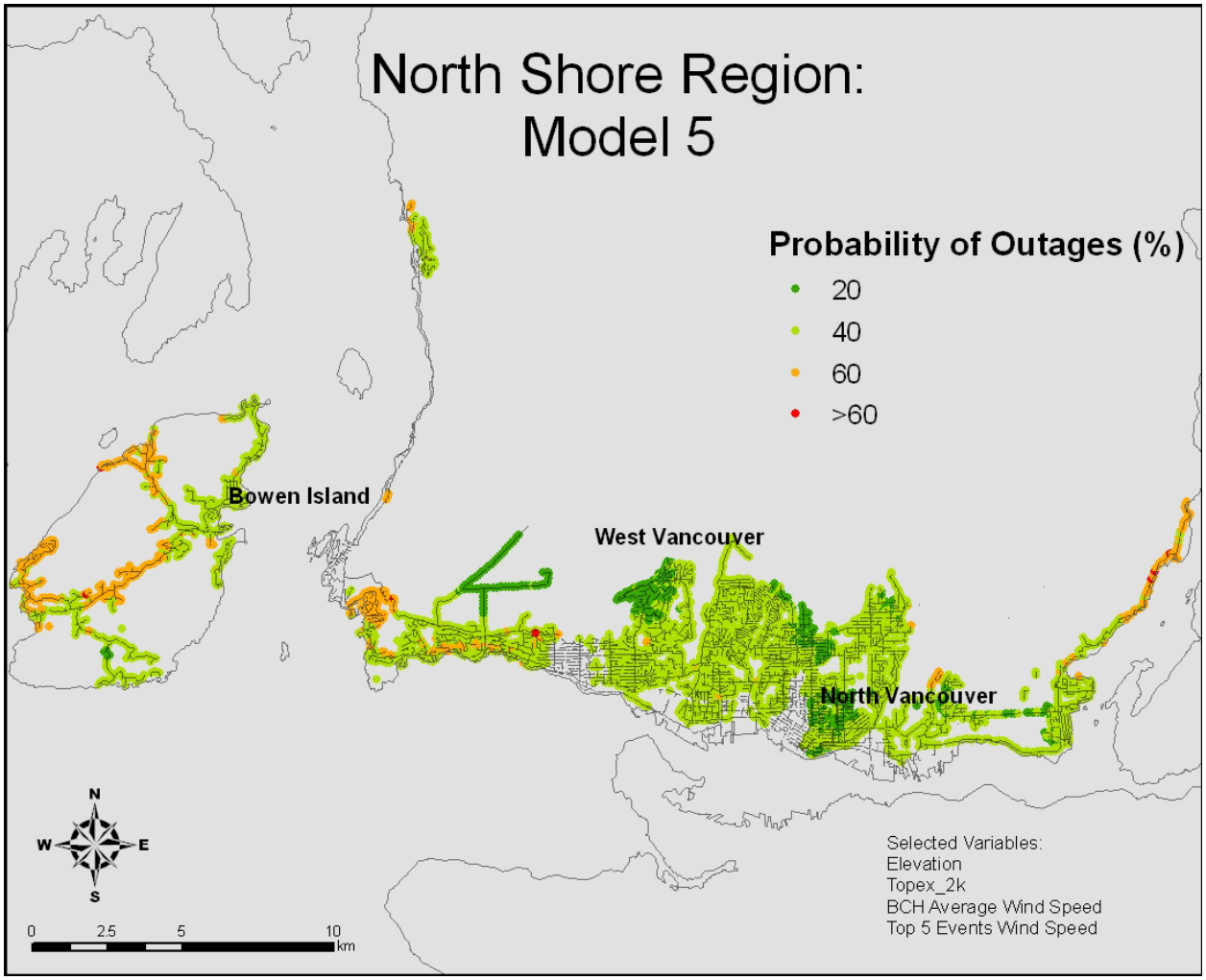


Figure 4.12. This map displays the probability of outages for the distribution network according to model 5. Areas in green have 20 to 40% more chances of experiencing an outage where areas in light orange and red have from equal or above 60% more chances of experiencing tree-related outages than other circuits.

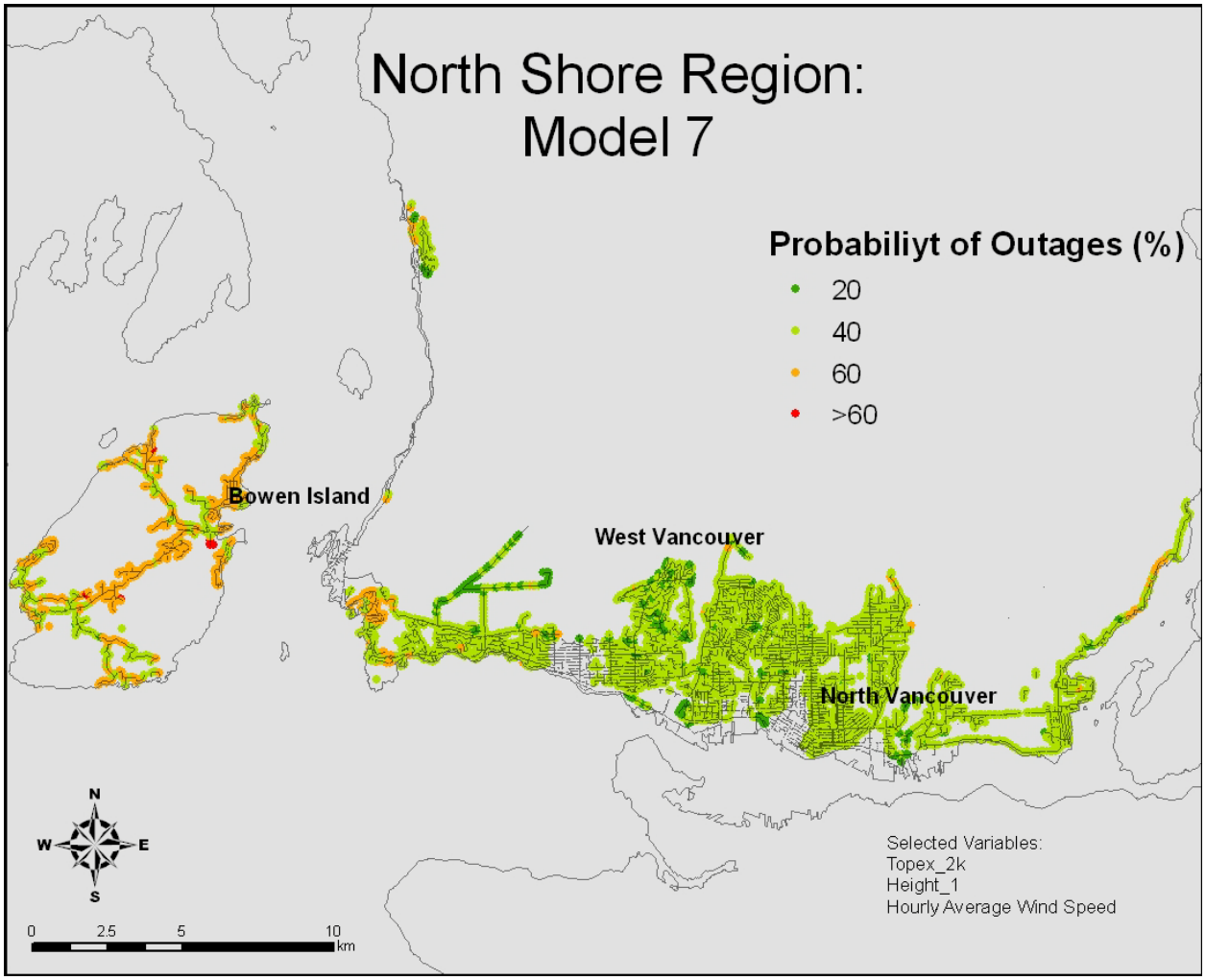


Figure 4.13. This map displays the probability of outages for the distribution network according to model 7. Areas in green have 20 to 40% more chances of experiencing an outage where areas in light orange and red have from equal or above 60% more chances of experiencing tree-related outages than other circuits.

4.14 Discussion

Adverse weather was responsible for almost 50 % of the outages from 2005 to 2009. This is a high proportion of outages compared to other studies. Guggenmoos (1995) found that fallen trees were responsible for most of the customer-hours lost in the period of 1978 to 1985 in areas supplied by the TransAlta Utility which covers areas in Canada and United States. Rees et al. (1994) studying outages in the Baltimore region found that of 3,000 outages, 98% were caused by fallen trees, fallen branches, and tree parts leaning onto lines. Effects of adverse weather conditions on natural hazards such as landslides (Guthrie et al. 2010) and windthrow (e.g.

(Mitchell et al. 2008) can be simulated using weather data from numerical weather prediction models. It should also be possible to simulate failures in electrical distribution infrastructure caused by adverse weather. Zhu et al. (2007) simulated number of outages caused by storms using empirical models. Their models under predicted the number of outages when compared to real data collected during the storms. However, to mitigate the direct effects of extreme weather is rather difficult and requires that structures are reinforce or replaced with more robust ones (e.g. Ulrich 1983). It is more feasible to address outages caused by fallen trees, which were the second highest cause of outages. Although fallen trees and fallen branches caused similar levels of outages, fallen trees affected double the amount of circuits in the North Shore District and left 10% more customers without power. Addressing grow-ins has been proved to be efficient, which reduces outages caused by branch growth towards the lines. Simpson and Bossuyt (1996) found that grow-ins outages were not significant in Brockton-US, managed by Eastern Utilities as their program has been going for 4 years previous to the data collection. On the other hand, tree failure has greater affect on the distribution reliability. In the previous chapter, fallen branches were responsible for 4% of the tree related outages while fallen trees caused 62% of the outages.

As was found provincially for the transmission system (Chapter 3), outages were more frequent in the winter. The period between the months of October to December is known to be the worst for outages in the distribution grid of BC (BC Hydro Corporation 2008). Winter months are known to produce strong storms frequently (Branick 1997). Labelle (2008) mentioned that November and December are the most critical months regarding outages. Storms bring precipitation rates up, which increases moisture content, and eventually reduces tree stability (Kamimura et al. 2009).

There were more outages in 2006 than the other years as result of a series of catastrophic wind/ snow storms (BC Hydro Corporation 2007). The decrease in the windthrow rate after 2006

onwards could indicate that BC Hydro is more effectively managing hazard trees through their vegetation management program or that the majority of unstable trees were windthrown by the 2006 storm. While BC Hydro has invested more money in tree hazard management since 2006, it seems more logical that 2006 was a very unique year (30 year returning period - (Read 2011)) regarding weather events, resulting in great windthrow damage and that the following years only the very unstable trees were windthrown.

Outages were clustered in a few locations. Lions Bay and Bowen Island are located close to the water. Scott and Mitchell (2005) found that proximity to the coast influenced the percentage of windthrow in Clayoquot Sound. Locally, valleys tend to channel winds and winds going perpendicular to slope cause more damages (e.g. Ruel, Pin & Cooper 1998) and this may explain the higher damage levels near Capilano, Lynn Valley, and Indian Arm. The latter three locations also have older, taller (Figure D.1. and Figure D.2. from Appendix D.), even-aged stands which also tend to experience more windthrow (Ruel 2000, Lanquaye-Opoku and Mitchell 2005, Mitchell and Lanquaye-Opoku 2009).

In the North Shore, lower voltage distribution circuits are less affected by outages than higher voltage circuits because of their locations. The 4 kV circuits are distributed in smaller pockets in more established urban areas which experience smaller wind exposure than the other locations (Wells 2011). In the transmission system, the opposite was true. Higher voltage transmission lines were less vulnerable to outages. This may have more to do with the spatial density of different voltage lines, rather than differences in line management. Lower voltage distribution circuits are clustered in the British Properties and east of Lower Lonsdale in areas with relatively low outage densities. In contrast, the 25 kV lines run exclusively on Bowen Island, which is also an area with a high density of outages.

Circuit phases experienced different number of outages. The high percentage of outages in 1-phase circuits is consistent with previous work by BC Hydro, where 1-phase fault accounted for 84 % of the total faults and 3-phase only 13% (BC Hydro Corporation 2008). Three-phase circuits run longer distances and usually in straight long lines, with a few clusters around the Lower Lonsdale area (Figure 4.4). In contrast, 1-phase circuits are more spread out and usually shorter often reaching the customer directly.

The availability of VRI data for the North Shore provided an opportunity to examine the relationship between stand attributes and tree-caused outages. Older and taller stands seemed to experience more outages than younger and shorter stands. Windthrow studies in cutblock edges found similar trend (Mitchell, Hailemariam & Kulis 2001, Mitchell, Lanquaye-Opoku 2004, Lanquaye-Opoku, Mitchell 2005,). On the other hand, validating windthrow mechanics models in Great Britain and Finland, Gardiner et al. (2000) found that the critical wind speed (to uproot or break) for Scots Pine or a Norway Spruce in Podzol soil increased with increasing trees height within stand. This suggests that taller trees within stands, behave differently than tall stands. Taller trees have had greater exposure to wind and access to resources than neighbouring trees. Competition between trees reduces windfirmness. Gardiner et al. (1997) measuring how tree spacing affects bending moments found that trees in wider spacing are more tolerant to winds than trees in small spacing sites. This could be a factor of the decrease in the height: diameter ratio experienced by previous thinned stands (Mitchell 2000b) as a factor to counterbalances the damping between neighbouring trees. There was no clear trend in the relationship between crown closure and outage frequency in the North Shore. However, in the two regression models where crown closure was selected, it had a positive coefficient, meaning that with other factors accounted for, denser stands are more likely to lead to tree failures.

Outages increased with stand age. On equivalent sites, older stands are often taller, and on the North Shore, height and age are well correlated (0.78). Older stands may also have more disease or defects than younger stands. Jalkanen and Mattila (2000) found that older stands in Northern Finland experienced more wind damage than younger stands. In contrast, Mitchell et al. (2001) found that wind damage was lower in older stands on Vancouver Island. However, on Vancouver Islands older stands are typically multi-aged and are often dominated by large dead-topped redcedar. The ROWs in the North Shore run through stands that originated following logging and wildfire in the late 19th and early 20th centuries as the Lower Mainland was being cleared and settled. Because of their logging and fire history, most of these stands are even-aged, but are composed of relatively long-lived, tall-growing species. Some stands are still in the self-thinning stage, while others are entering early maturity and understory re-initiation (e.g. Oliver and Larson 1996). It is expected that these even-aged forests will continue to experience more windthrow (and consequently more tree-related outages) until they develop a multi-age structure.

Outages were more frequent in topographically sheltered areas, but also increased with top-5 events wind speed. Adding in the general decline in outages with elevation and the spatial clustering of damage across the North Shore and it is apparent that the wind and terrain interactions are complex in this Region. The North Shore region is very irregular regarding its terrain and local wind patterns, a reality that was not captured in the MC2 output due to its low spatial resolution (4 km). Inlets and valleys of coastal BC are influenced by arctic outflows which cause wind speed acceleration and snow at low elevations (The Weather Network 2011). BCH_WS annual average wind speed and MC2 hourly wind speed maps do indicate faster winds for the southern tip of Bowen Island and the areas closer to the ocean.

The negative coefficient for precipitation in Models 2 and 7 was consistent with the contingency table results for this variable, but it was expected that outages would increase with precipitation.

Tree-related power outages are more numerous during the winter months (BC Hydro Corporation 2007) when precipitation is high, and wet soils are known to reduce tree stability (Kamimura et al. 2009). As noted previously, the climatic variables were coarsely gridded relative to the size of the study area. Also, the spatial clustering of damage in North Vancouver suggests exposure to winds off the ocean is the main determinant of vulnerability, and Bowen Island and Horseshoe Bay have relatively low rainfall.

The selected regression models were generally simple using a maximum of 4 variables to fit the outage dataset. With only one category of data, the topographic model had the best fit and the climate model the worst. Model 5 (Topographic-Climate variables) fits the data better than all the single or multi-category models. Considering the number of variables, this model has more variables than the other models which makes this a more expensive and complex model. When considering topographic or climate or stand variables (model 1, model 2, and model 3 respectively), topographic and stand data seemed to fit the outage dataset better when predicting outage locations. Topographic and stand data were combined and provided a slightly better fit. The combination of topography and climate variables improved the ability in separating low and high risk probability groups (e.g. Model 5). Adding stand variables (Model 7) did not improve model fit. Models fitting windthrow have been produced using tree, stand, topographic, and climate variables. Jalkanen and Mattila (2000) have used stand age and temperature to fit wind damage in Finland. Scott and Mitchell (2005) produced good models to predict windthrow in cutblock edge in the West Coast of Vancouver Island. Their windthrow models performed better (c-values of 0.58 to 0.82) than my outage models (c-values of 0.55 to 0.63). Lanquaye-Opoku and Mitchell (2005) tested the portability of windthrow models between different BC regions using topographic and climate data. Their models had c-values of 0.69, 0.75 and 0.79.

In spite of the moderate fit of the models, the maps displaying outage probabilities and actual outage densities (number of outages per length of line) were similar. The outage density maps indicate problem areas, the probability models and maps help to identify the factors that make these areas more susceptible. These maps could be useful tools for identifying locations which are more susceptible to tree-related outages. This information could be used to focus field assessments of risk factors, and to prioritize circuits for circuit maintenance, and produce local guidelines for line design and management in areas with high wind exposure. For utilities with limited vegetation management budgets this combination of tools would improve ROW vegetation management. Based on the results of my study, attention should be paid to southern tip of Bowen Island, Lions Bay, Horseshoe Bay, Capilano area, Upper Lynn Valley and Indian Arm.

It is clear that outage analysis and modelling has potential for improving vegetation management of ROWs but it is also clear that there are limitations and opportunities for further improvements. The outage dataset was collected recently (2004 to 2009) and in order to model these outages locations a vegetation dataset with information of the same period would simulate the actual tree fall and consequently outage reality. The spatial resolution of the climate data seemed to be too low to add much accuracy to the outage models for the North Shore. A different approach would be to predict specific outages using the outage dates from the outage history dataset and compare it to real data or high spatial resolution simulation from NWP for the specific weather events, rather than using annual climate statistics such as mean wind speed or top-5 wind speeds.

To achieve a low percentage of grow-ins requires good vegetation management in trimming branches and removing trees growing under the lines, and in predicting tree growth rates between treatment re-entries. The results for the North Shore suggests that BC Hydro's tree maintenance programs are generally effective at keeping lines clear, nevertheless, the number of

outages from fallen trees and branches suggests that there is room to improve assessments of hazard trees in the neighbourhood of the ROWs in some locations.

For future research, more information about local winds near the water could improve model fit. Furthermore, real climate data and higher spatial resolution models would be of help in modelling outage locations caused by trees. In terms of vegetation management, BC Hydro keeps a track of the dates (SAM) the vegetation maintenance was performed and this could be a useful predictor in the logistic regression.

4.15 Conclusion

This research demonstrated techniques for predicting locations of tree-caused outages using readily available and relatively low cost spatial information. Outage cluster analysis provided information about the areas most affected while contingency tables and models provide insights into the topographic, climate and stand factors that contribute to outage vulnerability. These tools could help vegetation managers in allocating labour and financial resources for vegetation management more efficiently. The stand variables that are associated with vulnerability (age and height) are consistent with other studies and provide some insights into the long term nature of vegetation management in heavily forested terrain. More accurate and up-to-date datasets would likely improve the performance of these models. Higher spatial resolution climate data should capture more localized wind and terrain interactions.

5.0 General discussion, recommendations, and conclusion

Fallen trees cause more outages than other factors such as vandalism, wildlife, and equipment failures in BC. Tree-related outages occur in seasonal patterns and in spatial clusters which provide insights into the causal factors. Understanding these patterns and the contributing factors could lead to more effective management of transmission and distribution grid.

Tree-related outages are more frequent on both the transmission and distribution grids during the winter months (November to February) when the precipitation rates are higher and winds are stronger. Line clearance and management priorities vary with line voltage and these result in different outage frequencies. At the provincial level, the higher voltage lines experienced very low numbers of tree-related outages, and this reflects the priority given to maintaining secure power supplies on the high voltage portion of the grid. Tree-related outages were more frequent in the lowest voltage portions of the transmission grid which are located closer to urban areas where a compromise is made between security of electricity supply and the amenity value of trees. The 69 kV ROWs are typically narrow and trees grow in close proximity to the lines. This increases the risk of outages and maintenance and repair expenses. Provincially, the areas with highest outage density were the Lower Mainland, Duncan, the stretch between Ucluelet and Parksville, north of Kelowna, north of Slocan, west of Prince George, and near Bella Coola. For the distribution system in the North Shore District, outage density per km is lower on the 25 kV portion of the system than on the 12.5 and 4 kV portions. Outage densities are highest on Bowen Island, Horseshoe Bay, Lions Bay, Capilano, Lynn Valley, and North Woodlands.

The areas of high outage occurrence provincially and regionally shared similar proximity to water bodies and complex topography. This can be attributed to winds coming from the ocean,

and channelling along water bodies. Winds also funnel through major valley systems. In both the provincial (transmission) and regional (distribution) studies, the top 5 annual wind speeds were better predictors of outage locations than mean annual wind speeds. Trees likely have lower resistance to wind loads in areas that are normally sheltered by terrain, but which are periodically exposed to high winds during storms.

Stand condition was taken into consideration in the regional analysis. Outage susceptibility increased with stand age and stand height. As second growth vegetation, the stands in the North Shore are growing rapidly and at high densities, and so will present a challenge for utility managers for the foreseeable future. The individual topographic, climatic and stand variables provided important insights towards understanding tree-related outages. In combination, in the form of logistic regression models, they can be used to produce maps of low to high vulnerability locations. The models ranged from poor to good fit. In the provincial analysis, the models fit the data well (c-values as high as 77) with relatively low lack of fit (HL Chi-square of 15.7). Regionally the model fit was poorer (c-values as high as 63), but the best model still had low lack of fit (HL Chi-square of 15.09). When mapped, the higher probability locations lined up with higher outage density locations.

There are a number of limitations and assumptions of this analytical approach that should be taken into consideration when considering application of study results. No stand-level information was used in the provincial/transmission system analysis. Tree-fall rates over the next 18 years will likely be different from the past 18 years since BC has just experienced a major mountain pine beetle outbreak. The stand-level information used for the North Shore/distribution system analysis does not contain information on stand health factors such as root disease, and this is not generally included in forest vegetation resource inventory labels. However, the

importance of stand height as a predictor indicates that long term mechanical stability of healthy stands should be addressed in ROW vegetation management programs.

Potential sources of errors in the provincial/transmission analysis include lack of accurate spatial coordinates for outages, coarsely gridded climate data, and a lack of vegetation cover data within the vicinity of the lines. This analysis could have produced better results if the outage dataset was provided in spatial format similar to the BC Hydro dataset. Potential sources of error in the regional/distribution system analysis include: the coarse spatial resolution of the climate dataset in this area of complex terrain and localized effects such as proximity to ocean/water bodies, and the quality of stand information in the more urbanized portions of the district.

It is recommended that BCTC/BC Hydro have their maintenance crews collect and report outage coordinates using a GPS unit during outage assessments. Incorporating land cover information provincially would enable more comprehensive modelling in the provincial analysis. As ROW width affects likelihood of falling trees contacting the lines, having ROW width information spatially would certainly improve the models for both provincial and regional modelling.

Both provincial and regional analyses would have benefitted from climate data with higher spatial resolution as localized effects appeared to be important factors in the outage locations. The resolution of numerical weather prediction models is improving. The challenge is in archiving the hourly forecast datasets over a period of several years, since they are very large amount of data. Interesting future research would be to analyze the weather behaviour during specific multiple outage events and to relate the passage of weather systems to the progression of outages across the system.

I conclude that outage location in transmission and distribution grids are driven by the same general factors, but that local wind and terrain interactions are important but hard to characterize.

Vegetation management plans should continue to reduce the risk of outages by eliminating hazard and danger trees from stands adjacent to power lines. The outage density and probability maps could be useful tools for locating circuits that are more susceptible to outages and in customizing local management and ROW design regimes. Since healthy trees in second growth stands can still have low wind stability, consideration should be given to expanding the edge tree management programs to include gradual stand thinning. ROW expansion or edge thinning treatments should be carried out with caution. While individual tree stability increases with time following removal of competitors, residual trees are more vulnerable immediately following removal of neighbouring trees. Models and maps of potential susceptibility should be used in conjunction with field assessments by experienced personnel when prescriptions are being prepared.

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Appendix A - Classification code for the sorting process of the outage history for BCTC analysis.

Table A.1. Outage classification code

Cause	Code	Description
wildlife	5	beaver
branch	0/3	branch blown over
other	0	unknown cause
snow	4	snow laden on trees / snowy weather
tree fallen	1	outages w/ specific location
tree-related	0/1	outages w/o specific location
weekend logger	6	weekend loggers

Source: BCTC non-spatial data (data compilation period 1990 to 2008). The outages were classified based on the description on the "Event Comment" column.

A.1. Tree outage assessment form

PACIFIC NORTHWEST TREE FAILURE REPORT

Available online at: http://w3/td/ma/vegetationnew/tdcorridor/doc/pacific_northwest_tree_failure_report_form.doc *To request a Users Guide please contact:* mailto:brian.fisher@bchydro.com

TREE INFORMATION

Genus _____

Species _____

Cultivar _____

Common Name Hemlock

Dbh (inches) 16 Height (ft) 70

Spread (ft) 10 Age UNKNOWN

Condition ☐1-dead ☐2-poor X 3-fair ☐4-good☐5-specimen

Crown Class X1-dominant☐2-codominant☐3-intermediate ☐4-suppressed

TREE FAILURE DETAILS:

1. Date of Failure (mm/dd/yyyy) MARCH13TH 2003
2. Time of Failure (24:00) N/A
3. Location of failure on tree (choose 1)
   - ☐ 1-Trunk _____ ft above ground _____ inches diameter
   - ☐ 2-Branch _____ ft from attachment _____ inches diameter
   - Height of attachment _____ ft
   - Branch angle at point of failure _____ Degrees
   - End weighted branch ☐ Yes ☐ No
   - X 3-Root failure
4. Site use (explain on page 2)
   - ☐ 1-undeveloped
   - X 2-low (intermittent vehicles / people
   - ☐ 3-medium (permanent structures, intermittent vehicles/people
   - ☐ 4-high (permanent structures, frequent vehicles/people)
5. Stand Type
   - X 1-natural☐ 2-planted☐ 3-mixed
6. Tree occurring (choose 1)
   - ☐ 1-alone (at least one crown diameter apart)
   - X 2-grove (less than one crown diameter apart)
   - ☐ 3-altered stand (new forest edge)

TREE STRUCTURAL DEFECTS:

7. Choose up to 3 in order of importance 1st: 13 2nd:___ 3rd:___

1-failed portion dead	8-embedded bark in crotch
2-multi trunks/codom stems	9-crook or sweep
3-dense crown	10-leaning trunk
4-heavy lateral limb	11-crack or split
5-asymmetrical (side heavy)	12-kinked/girdling roots
6-asymmetrical (top heavy)	13-none apparent
7-multibranching at 1 point	14-other

TREE STRUCTURAL DEFECTS:

8. Type of decay at failure (choose 1)
   - X 1-root rot
   - ☐ 2-heart rot
   - ☐ 3-sap rot
   - ☐ 4-heart rot and sap rot
   - ☐ 5-no decay noted
9. Extent of decay % cross sectional area (for root failure estimate % roots decayed)
   - ☐ 1-25% or less
   - ☐ 2-26-50%
   - ☐ 3-51-75%
   - X 4-76-100%

☐ 5-unknown

10. Fungal conks, etc near failure ☐ Yes X No
11. Other injury at failure location (choose 3) 1st:8 2nd:___ 3rd:___

1-mechanical	6-vehicle
2-lightning	7-fire
3-insect	8-none
4-animal	9-other
5-chemical	(explain on page 2)

12. Other injury, entire tree 1st:8 2nd:___ 3rd:___
(choose up to 3 in order of importance -- same options as 11)

Reference # _____ Report Date: MARCH 19 2003

TREE LOCATION 60L12 POLES 8-1 TO 8-2

Owner _____
Street Number _____
Street _____
City MISSION
Province / State _____

Site Category:
☐1-Residential -☐SF or ☐MF
☐2-Street☐3-Park
☐4-School ☐5-Highway
☐6-Parking Lot☐7-Mall
X 8-ROW☐9-Other

MAINTENANCE HISTORY:

13. Pruning - at failure location 1st: 7 2nd:___ 3rd:___
(choose up to 3 in order of importance)

1- heading cut (moderate)	4-lion tailing
diameter _____"	5-flush cuts
2- heading cut (severe)	6-root pruning
diameter _____"	7-no pruning
3-thinning cuts	8-other (explain page 2)

14. Pruning - entire tree 1st: 7 2nd:___ 3rd:___
(choose up to 3 in order of importance -- same as option 13)
15. Other maintenance (choose up to 2) 1st: 5 2nd:___

1-cable/hardware	4-cavity treatment
2-staking/props	5-not applicable
3-girdling wire/rope/etc.	6-other (explain page 2)

SOIL AND ROOT CONDITIONS AT SITE:

16. Restricted roots (choose up to 2) 1st 5 2nd:___

1-raised planter or bed	4-root cutting/trenching
2-container or boxed tree	5-not applicable
3-root barriers	6-other (explain page 2)

17. Irrigation

X 1-none	☐ 2-less than 1x per month
☐ 3-more than 1x per month	☐ 4-more than 3x per month

18. Ground cover under tree (choose 2) 1st: 4 2nd:___

1-bare soil	6-shrubs
2-mulch	7-mixed planting
3-turf	8-paving
4-native cover	9-other
5-herbaceous plants	

19. Soil in tree vicinity

X 1-good condition	☐ 2-compacted
☐ 3-saturated	☐ 4-dry
☐ 5-shallow	☐ 6-other (explain page 2)

20. Site topography changes (choose 2) 1st: 6 2nd:___

1-excavation
depth _____ ft
distance from trunk _____ ft
2-grade change - cut
3-grade change - fill
4-slope erosion
5-streambank erosion
6-not applicable

WEATHER AT TIME OF FAILURE

21. Wind Speed
☐ 1-low (less than 5 mph) ☐ 2-moderate (5 to 25 mph)
X 3-high (more than 25 mph)
22. Wind
X 1-gusty ☐ 2-steady
23. Wind in prevailing direction for season select direction
24. Wind direction related to branch
☐ 1-parallel X 2-perpendicular
25. Temperature (degrees Fahrenheit) 52 °F
26. Precipitation
X 1-rain ☐ 2-snow ☐ 3-ice ☐ 4-fog ☐ 5-none

Please submit photographs.

Briefly describe why you believe the failure occurred:

ROOT ROT THERE IS A SMALL AREA THAT IS AFFECTING HEMLOCK ONLY

Results of the tree failure (i.e. property damage, personal injury, etc.):

69kv kicked out

Damage estimate (cost of clean-up, other costs if known):

Not known

Additional information and comments:

There are a few hemlock that are dead and dying will follow up with removals .

Prepared by:

Certification #	**Pn-0463**		
Name	**Rod Crothers**	Title	**VEG MAINTENANCE COORDINATOR**
Company / Agency	**BC HYDRO**	Phone	**604-219-4420**

Please submit the completed form with any available photographs, and other supporting material to:

Brian Fisher, Strategic Coordinator - Distribution
Mike Guite, Strategic Coordinator - Transmission
BC Hydro Vegetation Maintenance, LMS-2
8475 - 128 Street, Surrey, British Columbia, V3W 0G1
E-mail: brian.fisher@bchydro.com
E-mail: thomas.wells@bctc.com
CC: norm@arbortech.bc.ca

This completed form may be forwarded by Bri
c/o PACIFIC NORTHWEST CHAPTER ISA
PO Box 811
Silverton, OR 97381

In CANADA mail to:or fax to (604) 275-9554
PNW TREE FAILURE REPORTING PROGRAM
c/o ARBORTECH CONSULTING LTD
4700 Windjammer Drive
Richmond BC V7E 4L6

This form may only be completed by an authorized assessor. For more information please contact Brian Fisher at (604) 543-4152, Norman HOL at (604) 275-3484, or Paul Ries at the PNW ISA Chapter office at (503) 874-8263. This form may be photocopied.

The information in this report will remain confidential, and will only be used to develop statistical and general information about tree failures by species and type of failure.

This document is adapted by Norman Hol, with permission from the California Tree Failure Reporting program as developed by A.M. Berry, L.R. Costello, and R.W. Harris.

Table A.2. Input layers and information carried by each layer

Input Layer	Attributes	Format
BCTC_1990-2008_CLASSIFIED OUTAGES_20110526th.xls	Outage records and information: Date, time, circuit id, substation ID, number of customers affected, hours of disruptions, event description, outage classified by cause	spreadsheet
Circuits based on the voltage	Locations and brief description	Vector - Line
Circuits_BCTC	Locations and brief description	Vector - Line
Mesoscale Compressible Community Model	Hourly information of wind speed, precipitation, temperature for the 5 year period of 2004 to 2009. Information about the top 5 events wind speed.	Vector - Point
Structure - (e.g. poles)	Information about the type of structure and which circuit it serves	Vector - Point
trans_substtations_Nov9	Area of operation of the substation.	Vector - Point
Elevation	Elevation data covering the province of BC	Raster file
Topex_2k	Topographic exposure measured in the 8 cardinal directions using a 2 km limit distance to the skyline and average to the location of interest.	Raster file
Slope	Steepness information data covering the province of BC	Raster file

Appendix B - Description of the outage density process – Step by step

Outage per length of line creation process:

a) Outage cluster + b) Line cluster = outage per length of line (sp1_copy.shp (c))

a) Outage cluster creation process
    a. Purpose: create a raster of the outage density for BC
    b. Process: Kernel Density
        i. Purpose: calculate outage density and output in raster format
        ii. Input shapefile: outage point shapefile (Outage Locations_and climate_variables.shp
        iii. Options:
            1. Cells size: 3493.811138 m
            2. Radius size: 29115.0928156579 m
            3. Unit output: km²
        iv. Output RASTER: out_dens_def1
    c. Process: Resample
        i. Purpose: resample cell size to line raster cell size for ratio operation
        ii. Input raster: out_dens_def1
        iii. Cell size: 4400.180078 m
        iv. Resampling technique: NEAREST
        v. Output raster: out_resamp
    d. Process: Reclassify
        i. Purpose: create classes using of outage density for easier interpretation (from double to integer values)
        ii. Input raster: out_resamp
        iii. Classification process: 0 to 5 from 5 classes of values
        iv. Output raster: out_class
    e. Process: Raster to Polygon
        i. Purpose: create polygons with the specific outage density classification

ii. Input raster: out_class
iii. Option: Simply value checked
iv. Output raster: out_class_vector1

b) Line cluster creation process
   a. Purpose: create a raster of the line density for BC
   b. Process: Kernel Density
      i. Input raster: all_kvs_merged
      ii. Options:
         1. Cells size: 4400.180078 m
         2. Radius size: 36668.167317406 m
         3. Unit output: km²
      iii. Output RASTER: line_dens_def1
   c. Process: Reclassify
      i. Purpose: create classes using of line density for easier interpretation (from double to integer values)
      ii. Input raster: line_dens_def1
      iii. Classification process: 0 to 5 from 5 classes of values
      iv. Output raster: line_class1
   d. Process: Raster to Polygon
      i. Purpose: create polygons with the specific line density classification
      ii. Input raster: line_class1
      iii. Option: Simply value checked
      iv. Output raster: line_class_vector.shp

c) Intersecting outages and line density spatial attributes
   a. Process: Intersect
      i. Purpose: the information of outages and line within the outage polygons were merged in one file.
      ii. Input shapefiles: out_class_vector1.shp and line_class_vector1.shp
      iii. Output shapefile: intersect3_20110526th.shp

b. Process: Field Calculator
    i. Purpose: calculate outage density per length of line
    ii. Input shapefile: intersect3_20110526th.shp
    iii. Process: create GC__OUT_LIN field and calculate GC_OUT (outage cluster) divided by GC_LIN (line cluster)
    iv. Output shapefile: intersect3_20110526th.shp

Appendix C - Hosmer and Lemeshow plot for the non-selected models fit in the North Shore outage dataset.

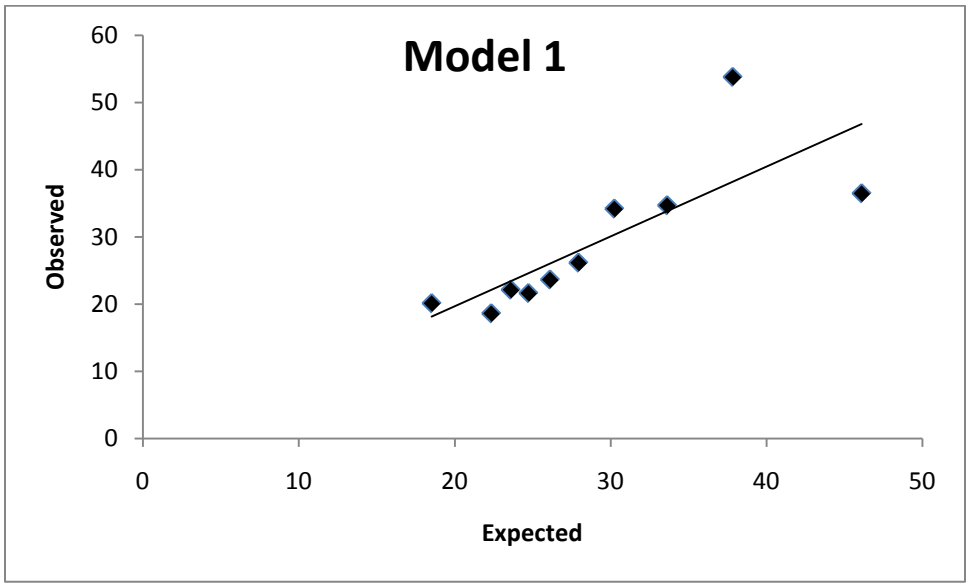

Figure C.1. Model 1: topographic variables only model. HL Chi-square test plotted (observed vs. expected).

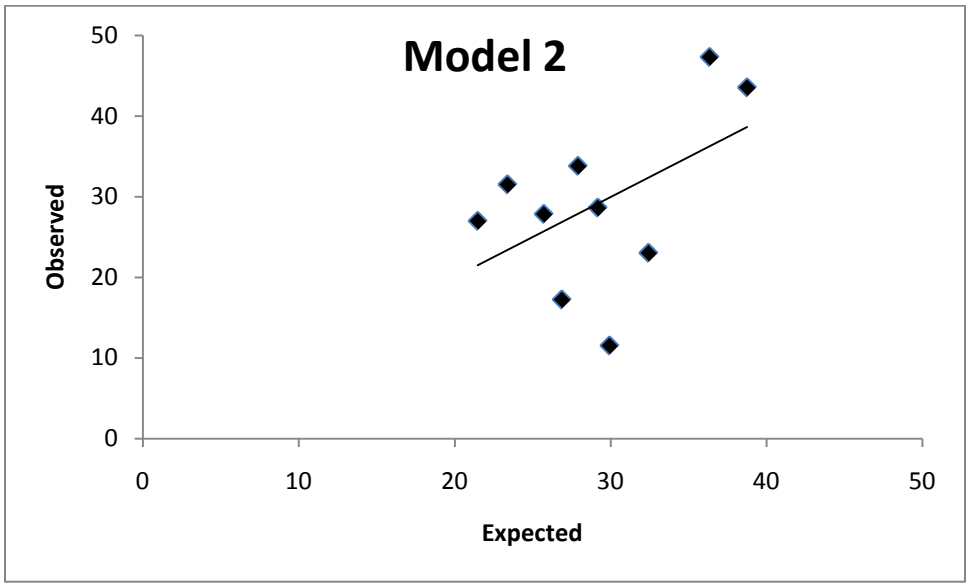

Figure C.2. Model 2: climate variables only model. HL Chi-square test plotted (observed vs. expected).

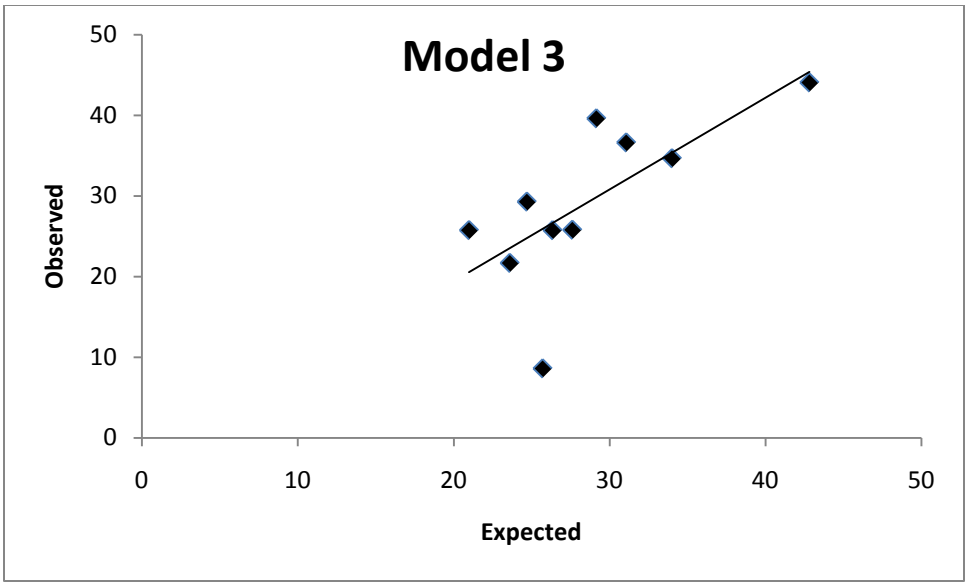

Figure C.3. Model 3: stand variables only model. HL Chi-square test plotted (observed vs. expected).

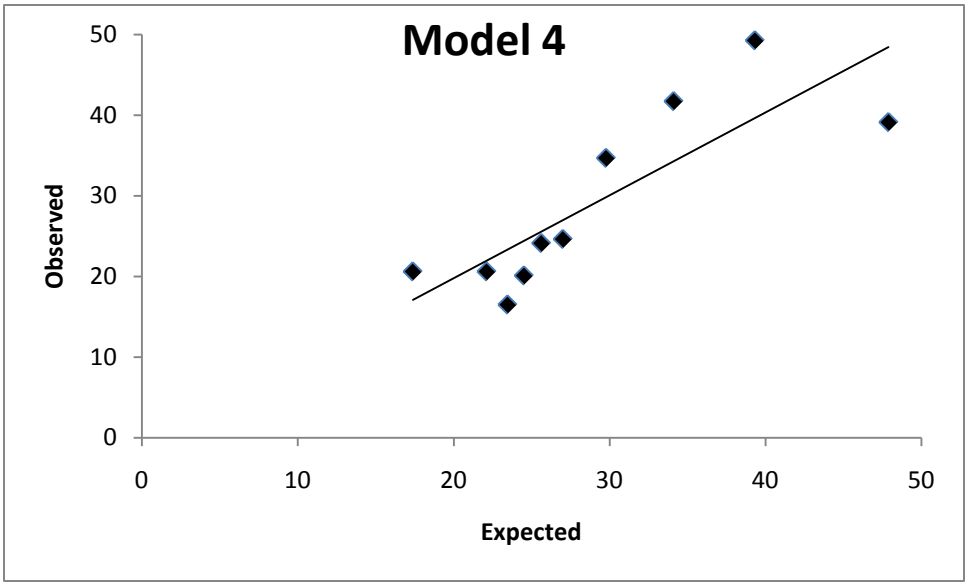

Figure C.4. Model 4: topographic-stand variables only model. HL Chi-square test plotted (observed vs. expected).

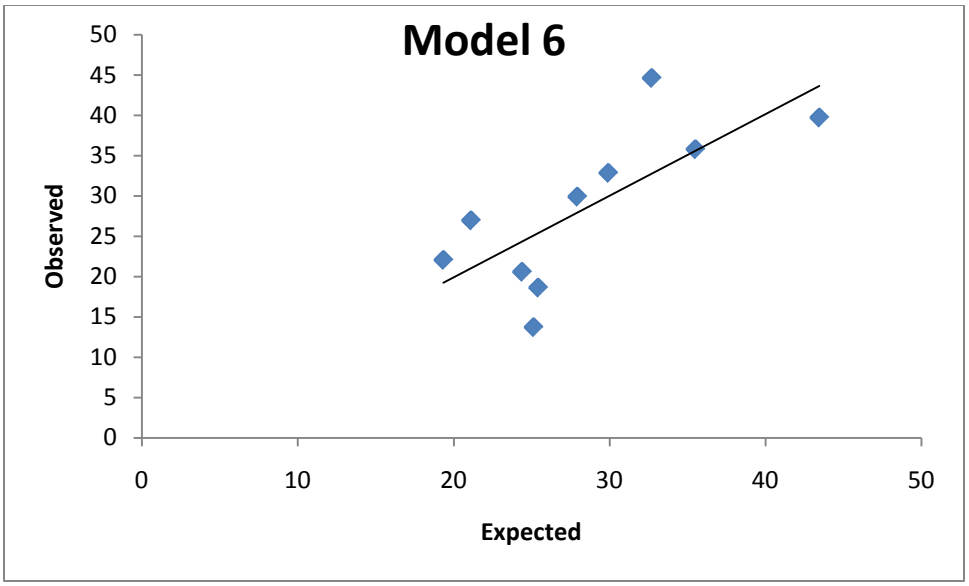

Figure C.5. Model 6: stand-climate variables only model. HL Chi-square test plotted (observed vs. expected).

Appendix D - Map distribution of the stand age and stand height for the North Shore analysis

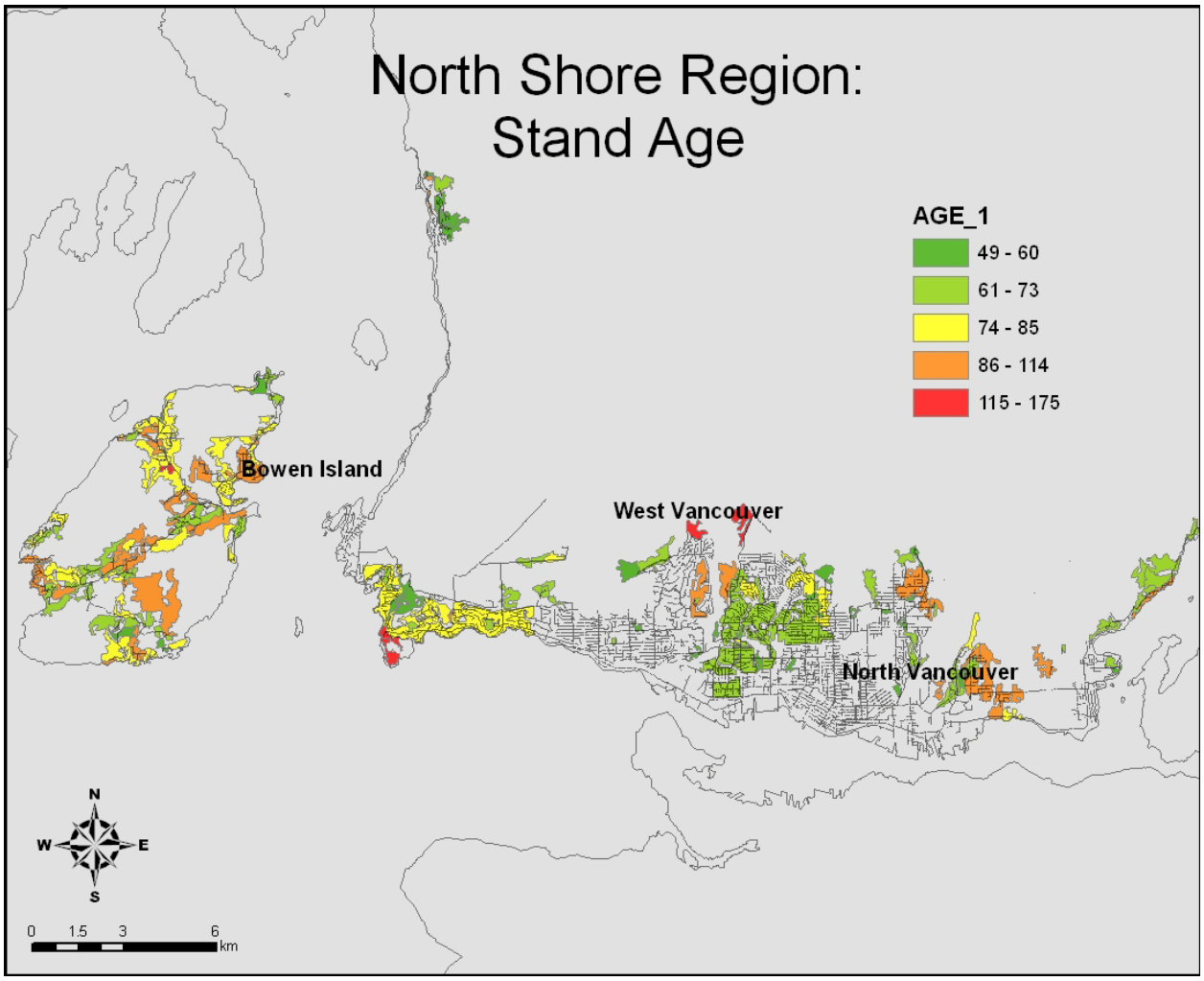

Figure D.1. Map of land cover by stand age. Areas in yellow, orange and red represent older stands. Bowen Island, Capilano area, and Deep Cove are populated with stands older than 80 years old.

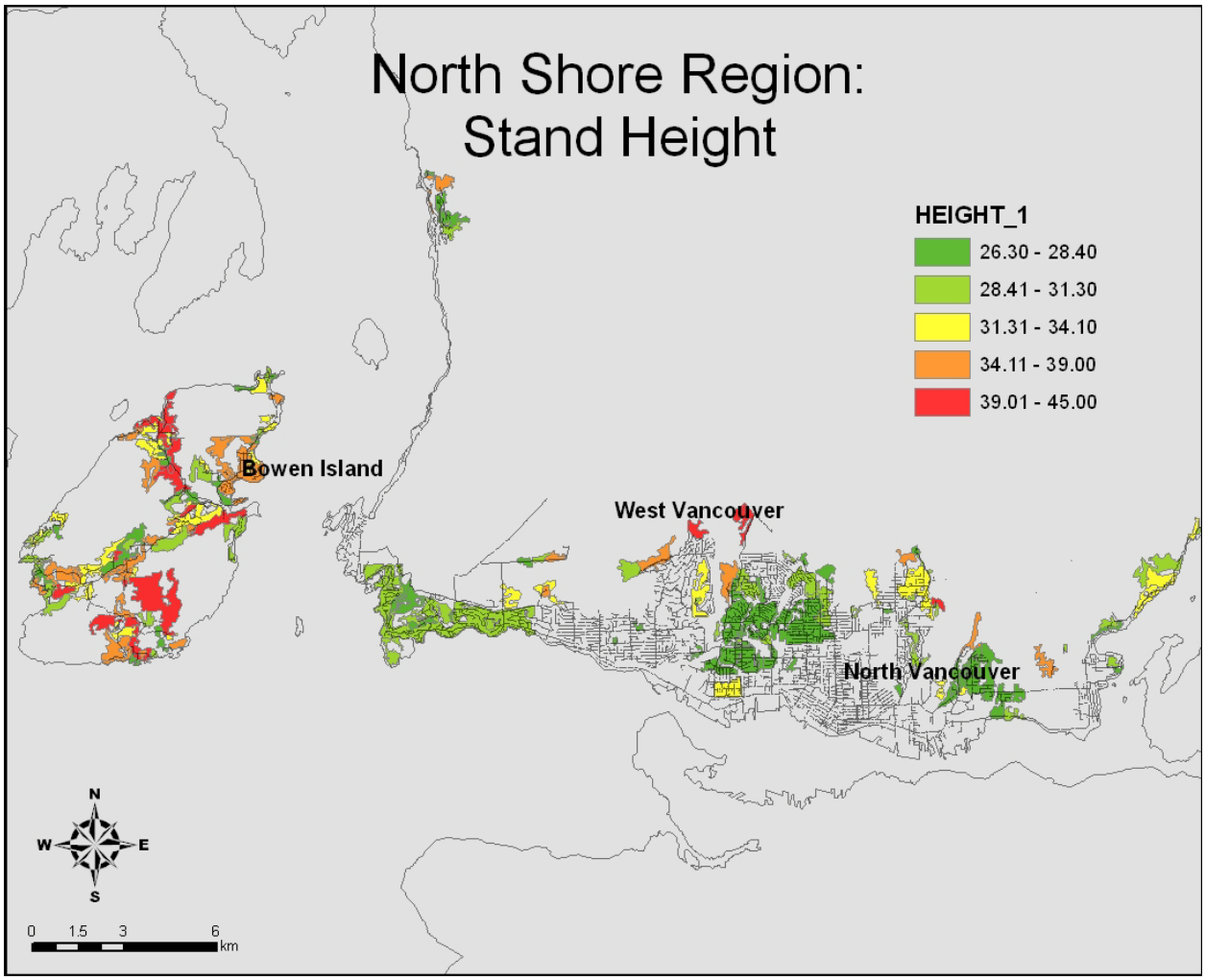

Figure D.2. Map of land cover by stand height. Areas in yellow, orange, and red represent taller stands. Bowen Island and Capilano area have tall stands, which tend to be more vulnerable due to their geographic locations.