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Road salt application planning tool for winter de-icing operations

William R. Trenouth [a], Bahram Gharabaghi [a,*], Nandana Perera [b]

[a] School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, Canada
[b] Computational Hydraulics International, Guelph, Ontario N1H 4E9, Canada

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SUMMARY

Road authorities, who are charged with the task of maintaining safe, driveable road conditions during severe winter storm events are coming under increasing pressure to protect salt vulnerable areas (SVAs). For the purpose of modelling urban winter hydrology, the temperature index method was modified to incorporate ploughing and salting considerations and was calibrated using winter field data from two sites in Southern Ontario and validated using data collected from a section of Highway 401 – Canada's busiest highway. The modified temperature index model (MTIM) accurately predicted salt-induced melt (R^2 = 0.98 and 0.99, RMSE = 19.9 and 282.4 m^3, CRM = −0.003 and 0.006 for calibration and validation sites respectively), and showed a demonstrable ability to calculate the Bare Pavement Regain Time (BPRT). The BPRT is a key factor on road safety and the basis for many winter maintenance performance standards for different classes of highways. Optimizing salt application rate scenarios can be achieved using the MTIM with only two meteorological forecast inputs for the storm event – readily available on-line through the Road Weather Information System (RWIS) – and can serve as a simple yet effective tool for winter road maintenance practitioners seeking to optimize salt application rates for a given storm event in salt vulnerable areas.

1. Introduction

Cold climates experience distinct challenges in terms of the prediction and management of both water quantity and quality, particularly how they relate to snow accumulation, redistribution and subsequent melt (Male and Granger, 1981; Rango et al., 2001; Semadeni-Davies et al., 2001; Dingman, 2002; Garen and Marks, 2005; Dewalle and Rango, 2008). This problem is particularly acute in urban areas, where winter road maintenance affects melt processes which in turn have direct safety and environmental implications (Male and Granger, 1981; Bengtsson and Westerstrom, 1992; Howard and Haynes, 1993; Canadian Council of Ministers of the Environment (CCME), 2011; Kilgour et al., 2013; Betts et al. 2014). In the context of this paper, 'winter road maintenance' refers to either snow ploughing or the use of de-icing agents, or a combination thereof. Roads salts – chiefly NaCl but also including $MgCl_2$ and $CaCl_2$ – are the most widely used de-icing agents and they work by lowering the melting point of snow and ice and, as a result of salt applications, snow melts and washes off of impervious surfaces as a concentrated brine. Approximately 5 million tonnes of road salts are applied annually across Canada, and given both its ubiquity and relatively low cost coupled with the pressing need to maintain driveable winter conditions, salt use is not likely to decrease in the foreseeable future (Environment Canada, 2013). At the same time, numerous studies have documented that both aquatic and terrestrial ecosystems can be adversely affected by exposure to high chloride concentrations associated with the typical use of road salts, and that drinking water supplies may also be put at risk (Novotny et al., 1999; Health Canada, 1999; CCME, 2011; Environment Canada, 2013). This underscores the need to apply road salts judiciously, but the complex interplay between temperature, salt, melt rate and commuter safety makes determination of the right amount an uncertain venture at best. In most cases, application rates are left to the judgement and experience of the practitioner (Guthrie, 2014 pers. comm.).

The recognition of these environmental concerns have prompted road maintenance authorities to employ various best management practices in order to minimize the deleterious effects of road salts (Salt Institute, 2007). However, the current understanding of the effects of salt applications on both melt rates and water quality is inadequate in large part due to a lack of winter

* Corresponding author at: Room 2417, Thornbrough Building, School of Engineering, University of Guelph, 50 Stone Road East, Guelph, Ontario N1G 2W1, Canada. Tel.: +1 (519) 824 4120x58451; fax: +1 (519) 836 0227.
E-mail address: bgharaba@uoguelph.ca (B. Gharabaghi).
URL: http://www.uoguelph.ca/~bgharaba/ (B. Gharabaghi).

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monitoring data, which in turn, owes itself to the challenges surrounding cold-season field activities. This hampers researchers who undertake any modelling of urban snow hydrology and water quality changes resulting from road salt applications. While the processes governing urban and rural snow hydrology share many commonalities, human impacts in urban environments alter snow characteristics (compaction and albedo), distribution (ploughed and bank areas) and change overall melt conditions (timing, rate and location), and hence produce conditions unique to urban areas (Ho and Valeo, 2002).

Given the difficulties in winter water quantity modelling, the simulation of urban winter water quality has received even less attention, and therefore the water quantity and quality aspects of winter de-icing operations warrant further study (Singh and Singh, 2001; Dingman, 2002; Valeo and Ho, 2004; Tartakovsky and Winter, 2008; Kumar et al., 2013). Elucidating both melt and washoff-related processes and developing a conceptually simple way to represent them in a salt management tool will assist maintenance practitioners with their task of applying the 'right' amount of salt. Loosely defined, the 'right amount' strikes a balance between the salt application density which results in a Bare Pavement Regeneration Time (BPRT) that is within the regulatory guidelines for the jurisdiction in which the road is situated, but which also exerts the minimum adverse environmental impact which is practically achievable (Novotny et al., 1999). The use of a simple model adds a systematic, methodological approach to the development of best management practices, and its use will also help to evaluate the efficacy of various salt application scenarios.

With the above considerations in mind, it is therefore the objective of this research to provide a new and improved methodology based on the TI method that incorporates considerations of road salting and ploughing. The efficacy of this novel tool is to be assessed through its application to a study site for which monitoring data has been collected. Such a tool would be indispensable for maintenance practitioners working to select both the optimized rates and timing of salt applications within a given storm event. The TI method was selected due to its relative simplicity and the ubiquity of its input meteorological parameters, both characteristics which lend themselves to rapid application by maintenance practitioners (Hock, 2003).

2. Background

Hydrologists have studied both thermally-induced and rain-on snow melt, and these two modes of energy addition to the snowpack are considered to be the primary processes governing snowmelt in rural areas (Garen and Marks, 2005; Walter et al., 2005; Kumar et al., 2013). However, the amount of research conducted on salt-induced urban snowmelt processes is somewhat more limited, and knowledge of this mode of melt generation is scant compared to melt under rural or forested conditions (US Department of Agriculture (USDA), 2004; Oberts, 2003). The addition of road salts lowers the melting point of snow, thereby contributing to the generation of melt, even at sub-zero temperatures. The wash off of road salt from trafficked areas has not received the same degree of attention from hydrologists owing in large part to its complexity, the challenges associated with winter monitoring and a subsequent lack of data (Oberts, 2003).

The energy balance (EB) and TI methods are the two main approaches used to model snowmelt under natural conditions. The EB method considers the energy exchange and heat transfer between the ground surface, atmosphere and snowpack in order to provide an estimate of snow melt (Walter et al., 2005). However, one of the basic problems in applied snow hydrology is that many of the meteorological parameters required to satisfy the energy budget calculations may not be conveniently available for use (Hock, 2003; Walter et al., 2005). Furthermore, complete EB calculations can be rather cumbersome for the uninitiated, and a simpler approach that can be rapidly applied by highway maintenance managers would be more useful. As an alternative, the TI method requires only a single meteorological input parameter – air temperature – in order to estimate snowmelt in a hybrid statistical/quasi-physical sense (Ohmura, 2001; Anderson, 2006). A precursor to the temperature index method, the degree-day method, uses either the daily mean or maximum air temperature in conjunction with a daily time step in order to carry out snowmelt calculations (Singh and Singh, 2001). While the physically descriptive EB modelling approach can reasonably be expected to provide better estimates of snowmelt compared to the TI method for a given location with high-quality data, when the models are applied with operationally available data across a large watershed, the relative accuracy of results is unclear. Anderson (2006) concluded that it has yet to be shown that an EB model will significantly improve overall results for applications such as winter riverine flow forecasting. The movement of snow within a catchment has a direct bearing on the timing and rate of melt, and can be as important to the successful simulation of melt as the selection of the melt equation itself. The conceptual framework for some of these processes are also considered.

2.1. Snow depletion curves

Snow depletion curves are used to upscale point snowmelt estimates to larger scales. Estimation of the percentage of an area covered by snow is required in order to determine the fractional area of a catchment over which energy exchange between the atmosphere, ground and snowpack is taking place. Snow depletion curves are also used to partition the relative amount of rain falling on bare ground in the case of rain-on-snow. In short, application of the areal depletion curve concept is used to describe the relationship between the areal extent of snow cover relative to the total area under consideration (Luce and Tarboton, 2004; Anderson, 2006).

In undisturbed systems like open fields and forested areas the areal coverage of snow decreases according to the areal depletion curve, and once melt begins to occur new snow can fall over areas that are partially bare (Cazorzi and Fontana, 1996). The specific pattern of areal depletion within a catchment is confounded by topographic heterogeneity, as well as irregularities in both the depth and density of wind-blown, redistributed snow. For example; redistributed snow tends to accumulate at greater depths in vales, ditches and other depressions, while upland areas are more likely to become exposed due to redistribution by wind (Burkard et al., 1991). Furthermore, when considered in the context of ploughed, trafficked areas, areal depletion is a much more gradual process than that which exists as a result of the mechanical movement of snow (i.e. minutes-to-hours compared to days-to-weeks). Due to both the complexities and application limitations of the areal depletion concept, it was decided that typical simulation of this process would be foregone as the required added complexity induced by inclusion of areal depletion concepts was not justifiable based on anticipated improvements to model performance. Instead, the authors opted to consider areal depletion on a binary basis; when snow is moved to the banks and the road surface melts, then the road surface is considered to have 0% snow coverage remaining, and the banks have 100% snow coverage remaining until such time that the banks have also melted.