Snowmelt modelling aspects in urban areas

Roxana-Gabriela Dobre\textsuperscript{a,b}, Dragos Stefan Gaitanaru\textsuperscript{a,⁎}, Constantin Radu Gogu\textsuperscript{a}

\textsuperscript{a}Groundwater Engineering Research Center, Technical University of Civil Engineering of Bucharest, Lacul Tei Bvd., no. 122 - 124 RO 020396, Romania
\textsuperscript{b}Mathematics and Computer Science Department, Technical University of Civil Engineering of Bucharest, Lacul Tei Bvd., no. 122 - 124 RO 020396, Romania

Abstract

Urban winter hydrology is generally poorly understood, despite the large number of cities which have annual seasonal snow cover and there are only few studies about urban snow and snowmelt rates in the cities. Two specific factors affecting the snow melting rate in urban areas are the degree of urbanization and the urban snow distribution. The net radiation balance of urbanised catchments differs from their rural counterparts. The choice of a snowmelt model for a particular application depends on data availability and snow characteristics. A review of attributes of common snowmelt models is presented for evaluation and selection of the best suited model for simulating snowmelt in a specific area. In snowmelt computations, the challenge is to identify a suitable model for the heterogeneous urban conditions from the existing model categories as TIM, EBM, or their combination as a hybrid method. For rural environments, empirical methods (TIM) have been demonstrated to reproduce a large part of the snowpack variations at both open and forested areas. For heterogeneous urban environments, it is necessary to apply an EBM in order to take into account all the characteristics of urban snow. Snow properties such as density and albedo vary both between urban and rural areas as well as between different urban locations belonging to the same urban agglomeration.

© 2017 The Authors. Published by Elsevier Ltd. Peer-review under responsibility of the scientific committee of the Urban Subsurface Planning and Management Week.

Keywords: urban snowmelt; energy balance; snow water equivalent; flood

⁎ Corresponding author. Tel:+40 746 961 119
E-mail address: dragos.gaitanaru@utcb.ro
1. Introduction

Urban snowmelt characteristics differ from those of rural environments. While there is a fair number of studies of snowmelt modelling for rural areas, there are limited efforts focusing on urban winter hydrology. Basic approaches used to model snowmelt are: the energy balance model (EBM) that requires detailed description of each term of the mass or energy balance equation in order to simulate the energy fluxes within the snowpack, the Temperature index model - TIM (empirical approach) in which air temperature is used to index the energy fluxes, and the combination of these two model approaches as a hybrid method.

For open areas the accuracy of EBM is well-established [1]. EBM is more complex to be implemented and usually needs more input data sets than TIM. For operational forecasting, it is more realistic to apply TIM due to the difficulty to predict several meteorological variables used by EBM for several forthcoming days [2]. The snowmelt estimations for a heterogeneous urban environment cannot be adequately determined by using TIM because those models assume a homogeneous snowpack and a heterogeneous snow coverage.

Several snowmelt calculation schemes have been developed for catchment hydrology calculations. Examples of EBM approaches are ESCIMO [3]; SNThERM [4, 5] and SnowMelt-R [2]. TIM approach includes SRM [5, 9], MIKE SHE [10], WINTER, ETI and COMBI [11-13]. Examples of the third, hybrid kind of approach are Snow -17[1], SWAT [6, 7] and HEC 1 [8].

Even though urban hydrology principles assume that the processes and factors governing both urban and rural snow hydrology are the same, the urban snowmelt models must incorporate the characteristics of urban snow that differentiate it from the snow outside the urban areas. Few urban snowmelt models use these characteristics. Within the EBM category, examples of these are HSPF [14], USM [15], GUHM [16], and SDM [17-19]. Urban conditions are also taken into account also TIM and hybrid model approaches. Within the TIM category, we mention MU (MOUSE RDII) [20]. EPA SWMM [21] is a hybrid model type. This study has identified several literature reviews on snowmelt modelling for rural areas [5, 22], but only one considering urban conditions [23].

The snow characteristics, its distribution and the snowmelt conditions in urban environments are related to land use and to the snow handling practices. Urban snow distribution depends on the initial snow distribution and location, the land use (houses, apartments, streets, etc.), the type of snow cover (snow piles, snow on road shoulders, snow on sidewalk edges, snow in open areas, etc.) and the land use after snow redistribution [18, 23-25]. Snow is removed from streets, front yards and parking lots and piled up near snow-free surfaces. Large amounts of snow are transported away from downtown to special city snow dumps. To what extent snow is transported, depends on the cities’ design and as well on the funds allocated for snow handling. Several studies [26, 27] have shown that the snow density and albedo vary both between city and countryside as well as a function of the land use. Also, urban elements such as vehicle traffic and buildings can influence the energy balance of the snowpack into the city.

The objective of the present study is to review and compare different snowmelt models based on different snowpack characteristics in and outside the cities.

2. Snowmelt modelling aspects

In snowmelt computations, the empirical models (TIM) are commonly used to simulate a large part of the snowpack variations in open and forested areas. The TIM and hybrid methods needs the least number of types of data inputs. EBM require many input data in order to describe the physical processes of each component of the energy balance, but EBM are considered more accurate than TIM [1, 11].

Walter et al., 2005 [2] estimate the energy budget components using the maximum and the minimum daily air temperature, as most of the TIM are running. The results showed a good agreement between observed and predicted snow water equivalent values so the use of mechanistic snowmelt modeling approaches in hydrological models could be encouraged.

Empirical models (TIM) simulate a large part of the snowpack variations in open and forested areas. Even EBM usually need more input data sets, energy based Snowmelt runoff modeling has been developed mainly for surrounding areas of cities in cold regions, where snowfall constitutes a significant quantity of the annual precipitation [2, 3 and 11]. Few studies focus on the urban regions in cooler or Alpine climates with significant snowfall and snowmelt [19,
In urban catchments in cold climate regions, characterized by seasonal freezing temperatures and temporary snowpack, there are three main phases of snowmelt during the transition from winter to spring [25]:

- Snowmelt on roads due to snow handling, including the application of de-icing salts or direct heating;
- Early snowmelt where snow is in transition from cold to warm and the liquid water can be re-frozen or stored in the snowpack;
- Late snowmelt, possibly in combination with rainfall, where melt at the surface is quickly released as runoff from the base of the snowpack.

### 2.1. Snow Energy Balance

The snowmelt rate is determined by the net energy flux to the snow pack [1]. The energy balance for a snow pack can be expressed as

$$ E = R_n + H + L + A + G $$

where \( E \) is the energy available for snowmelt. The following fluxes are taken into account: the net radiation \( R_n \), the sensible heat flux \( H \), the latent heat flux \( L \), the advective energy supplied by solid or liquid precipitation \( A \) and the soil heat flux \( G \). All the energy flux densities are expressed in [W.m\(^{-2}\)].

The components of the surface energy balance equation and the snowmelt rates can be calculated using the available meteorological variables (i.e., air temperature, precipitation, relative humidity, wind speed, air vapor pressure, incoming shortwave radiation or incoming longwave radiation) based on published approaches by [2, 3, 25, 26, 32].

The snowpack energy fluxes are highly influenced by the urban environment. The urban topography affects the radiation exchanges between the snowpack and the atmosphere. Factors such as the longwave radiation of buildings, full-sun/shadowed effect and the snow albedo variability have a high influence on snowpack energy fluxes of the urban environment [18, 19 and 26].

#### 2.1.1. The shortwave radiation

The net solar radiation is calculated by using the following formula:

$$ R_{ns} = (1 - \alpha) \cdot R_{in,s} $$

where \( \alpha \) represent the albedo [-], \( R_{in,s} \) is the incoming shortwave radiation and \( R_{ns} \) is the net shortwave (solar) radiation [W.m\(^{-2}\)]. [32].

The shortwave radiation is lower in the city than outside the city due to the impurities of the snow, the cloud density above the city, and the fact that a large part of the snow-covered area is affected by human activity. The snow albedo variation is related to the amount of shortwave radiation adsorbed by the snowpack. As consequence, the snow albedo is lower in the city than in the countryside. Urban snow albedo ranges from values similar to undisturbed rural snow: from 0.8 for fresh dry snow to 0.4 for wet melting snow. In the inner city, albedo lowers dramatically to around 0.2, which is equivalent to bare soil. The difference between the snow albedo of rural and urban environments is reported in literature to be to be about 0.2. This means that when the mean solar radiation is 200 W·m\(^{-2}\), the daily snowmelt is about 10 mm higher in the city than in rural environments [18].

#### 2.1.2. The longwave radiation

Assuming that the snow emissivity is close to 1, the net longwave energy can be calculated by using the following equation

$$ R_{nl} = \varepsilon \sigma (T_{ak})^4 - \sigma (T_{sk})^4 $$

(3)
where $R_{\text{nl}}$ is the net longwave radiation [W·m$^{-2}$], $\varepsilon$ is the emissivity of the atmosphere [-], $T_{\text{ak}}$, $T_{sk}$ are the air temperature and the surface snowpack temperature [K], and $\sigma=5.87\times10^{-8}$ W·m$^{-2}$·K$^{-4}$ is the Stefan-Boltzman constant [32].

In order to take into account the influence of clouds, that increase the emissivity of the atmosphere, and the influence of trees, Dingman proposed the following equation for the calculation of the atmospheric emissivity [32]:

$$\varepsilon = (1 - F) \cdot [(1 - 0.84 C) \cdot (0.83 - 0.18 e^{1.54 e - 1}) + 0.84 C] + F$$

where $F$ is the fractional forest cover [-], $C$ is the fractional cloud cover [-] and $e_a$ is the air vapor pressure [hPa].

For air temperatures below freezing, the snow surface is able to emit more longwave radiation than it receives. Clean snow emissivity is about 1 so it is higher than the emissivity of the air (around 0.8) under clear skies. The air emissivity increases up to 1 with an increasing cloudiness.

For air temperatures above freezing, the incoming longwave radiation can be greater than the outgoing longwave radiation which has an upper limit (about 312 W·m$^{-2}$) corresponding to a maximum temperature of 0°C with $\varepsilon=1$ [25].

Buildings gain longwave radiation and emit radiation at rates which are determined by their emissivity and temperature. The influence of buildings on the net longwave radiation decreases considerably under cloudy skies. It was found that two-storey houses influenced the net longwave radiation up to 10 m distance from the buildings. Also, when the sky was clear, the longwave radiation input into the snowpack located at 2 m from a building could increase by 100 W·m$^{-2}$, which corresponds to an increased melt rate of 25 mm·day$^{-1}$ [18]. Buildings have the highest influence over the radiation budget on sunny days when there is obvious shading along northern walls and heating of the southern walls. Under cloudy skies, shortwave radiation is restricted to diffuse radiation and incoming radiation is similar both on the north and south sides of the buildings. Incoming longwave radiation and diffuse solar radiation near walls are limited to that area of the sky dome that is not obstructed by buildings [25].

2.1.3. Turbulent fluxes

Because the atmospheric conditions are less uniform within a city than in open spaces, turbulent fluxes of sensible heat (that depend on the wind speed, the snow surface temperature, and on the air temperature) and latent heat (that depend on the wind speed, the air vapour pressure, and the water vapour saturation pressure at the snow surface) should be higher in cities than in rural areas. This assumption is valid for streets, which are cleared of snow and for roofs, but not for yards and parks which may be not exposed to the wind [3, 18 and 32].

2.1.4. Snowmelt rates

Urban snow has a higher net radiation $R_n$ (the sum between the net shortwave $R_{ns}$ and the net longwave radiation $R_{nl}$) absorption than rural snow of the same age that corresponds to an increased daily melt. Also the location affects the snowmelt rates: in the downtown part of the city the snow melted away faster than at the other sites [18 and 25].

The snowmelt rates are calculated for a period $\Delta t$ if $T_{sk} \geq 273.16$ K by using [3]:

$$M = \frac{E \cdot \Delta t}{c_i}$$

where melting heat of ice is $c_i=3.33725\times10^5$ J·kg$^{-1}$.

2.2. Others factors affecting the urban snowmelt process

The snowmelt process is also affected by frozen ground, the urban soil type or by pollution.

An important aspect in modelling snowmelt infiltration is that a frozen soil layer generally increases the amount of snowmelt runoff by decreasing the soil permeability. Frozen soil impedes the water infiltration, reduces soil
moisture recharge and restricts deep percolation [29]. In practice, frozen ground acts as a near impervious surface; infiltration of snowmelt into the frozen ground is minimal and can be assumed to be negligible.

Compared to rural areas, urban soils suffer heavy compaction due to activities such as construction, traffic and modification of the original soil stratification, resulting in a reduction of the soil infiltration capacity. Urban areas consist of both permeable and impermeable surfaces. Usually the impermeable surfaces are largely snow free (roads, driveways or parking lots). As a consequence, the permeable areas contribute mostly to runoff at the beginning of the snowmelt process. Urban soils tend to become progressively saturated and frozen upon snowmelt, which results in reduced infiltration capacity and overland flow [18, 19 and 27].

Pollution disturbs the snow albedo. Near the roads the snow shows a low albedo due to contamination (its black appearance), accelerating the process of snowmelt [25]. Among all the anthropogenic activities in urban areas, traffic is one of the strongest sources of pollution, particularly with respect to heavy metals. When it snows, atmospheric pollutants can be absorbed by the snow, eventually contributing to the contaminated water runoff during snowmelt. Dust and other pollutants on the impervious surface in cities are important components in snowmelt, accompanying the process of runoff. Also, road maintenance practices, including spreading of traction and deicing agents (e.g., grit or gravel, road salts) will have an impact on the snow properties [33].

### 3. Overview of snowmelt algorithms

In order to achieve accurate modelling results of the snowmelt process in urban areas, a classification of snow cover made for a selected number of studies is presented by Table 1. The most dominant types of urban snow formations are the snow piles and the natural snow cover on pervious areas. Others include snow on road shoulders, snow on rooftops, and snow near buildings or walls. The snow redistribution is the most influential activity affecting the snowmelt process. Snow is removed from impervious areas (e.g., roads, sidewalks, pathways, parking lots, roofs, etc.) and transported to other locations within or outside of the urban area [18, 23-25].

<table>
<thead>
<tr>
<th>Snow distribution</th>
<th>Observation</th>
<th>Parameters</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow precipitation</td>
<td>Luleå, Sweden 1979</td>
<td>α, R_{in,s}</td>
<td>[18]</td>
</tr>
<tr>
<td>Amount transported away</td>
<td>Snow distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow piles</td>
<td>[m³]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Untouched snow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Melted snow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piles</td>
<td>Luleå, Sweden 1998</td>
<td>SCA, ρ, α, h</td>
<td>[25]</td>
</tr>
<tr>
<td>Other</td>
<td>Land use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piles</td>
<td>Calgary, Canada 2005</td>
<td>ρ, h</td>
<td>[24]</td>
</tr>
<tr>
<td>Road shoulders</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sidewalk edges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open areas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow pile</td>
<td>2015</td>
<td>ρ, α, h,</td>
<td>[23]</td>
</tr>
<tr>
<td>Snow bank</td>
<td>initial snow location</td>
<td>W (normal, highly disturbed, disturbed)</td>
<td></td>
</tr>
<tr>
<td>Natural snow pack</td>
<td>land use after snow redistribution</td>
<td>R_{in,s} (normal, snowpack shape, shadow effect)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>R_{in,l} (normal, affected by structure)</td>
<td></td>
</tr>
</tbody>
</table>

Note. The parameters from snowmelt models are: h is snow depth [m], ρ is snow density [kg·m⁻³], α represent the snow albedo [-], W is wind speed [m·s⁻¹], SCA is snow cover area, R_{in,s} is incoming shortwave radiation [W·m⁻²], R_{in,l} is incoming longwave radiation [W·m⁻²].

There are many models that attempt to predict snowmelt rates, runoff, and infiltration from snowmelt. The selection of different types of applications depends on practical requirements. Initially, snowmelt simulation algorithms were point models (Snow-17, ESCIMO, SNThERM, SDM, etc.). They were extended to lumped or to
semi-distributed models (EPA SWMM, MU- MOUSE RDII, MIKE SHE, etc.) and to distributed watershed models as Snow-17 and GUHM. A main concern is that distributed models are data intensive and need high quality data. As consequence, too many parameters could be altered during the calibration phase. Semi-distributed models lump meteorological variables and physical parameters into sub-basins, which makes them more easily to set up and require shorter computing times. Table 2 gives an overview on several snowmelt calculation schemes of varying complexity, applied for rural and urban areas and using different time steps. TIM and hybrid methods need, as data input, time series of precipitation and temperature. These suit very well for forested basins without a significant topographic variation [5]. The remaining models of Table 2 are based on EBM and require additional predictive data (e.g. relative humidity, wind speed, cloud cover, radiation, etc.). When no measured radiation data is available, the net radiation can be estimated using available meteorological data [3].

In order to have accurate results of melt rates and snowmelt runoff for urban areas, the first step is to quantify the uneven snow distribution in cities and to incorporate it into the snowmelt model. Because physical based models are more robust to predict under heterogenous conditions, most of the studies that simulate urban snowmelt are based on EBM.

### Table 2. Overview of snowmelt model characteristics in selected studies

<table>
<thead>
<tr>
<th>Model</th>
<th>Model type</th>
<th>Time step</th>
<th>Parameters</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>General snowmelt models</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESCIMO</td>
<td>EBM</td>
<td>Hourly</td>
<td>(T_a, P, RH, W, \alpha, \varepsilon, R_{in,s}, R_{n,s})</td>
<td>[3]</td>
</tr>
<tr>
<td>SnowMelt-R</td>
<td>EBM</td>
<td>Daily</td>
<td>(T_a, P, RH, W, C, F, S, A, J, DL, \lambda, \alpha, \varepsilon)</td>
<td>[2]</td>
</tr>
<tr>
<td>SNTHERM</td>
<td>EBM</td>
<td>Daily</td>
<td>(T_a, T_d, P, RH, W, C, \varepsilon)</td>
<td>[4,5]</td>
</tr>
<tr>
<td>SRM</td>
<td>TIM</td>
<td>Daily/Hourly</td>
<td>(T_a, P, RH, W, R_n, SCA)</td>
<td>[5,9]</td>
</tr>
<tr>
<td>MIKE SHE</td>
<td>TIM</td>
<td>Daily</td>
<td>(T_a, P, C_M)</td>
<td>[10]</td>
</tr>
<tr>
<td>WINTER</td>
<td>TIM</td>
<td>Daily</td>
<td>(T_a, P)</td>
<td>[12,13]</td>
</tr>
<tr>
<td>ETI</td>
<td>TIM</td>
<td>Hourly</td>
<td>(T_a, R_{in,s}, \alpha)</td>
<td>[11,13]</td>
</tr>
<tr>
<td>COMBI</td>
<td>TIM</td>
<td>Daily/Hourly</td>
<td>(T_a, P, R_{in,s})</td>
<td>[13]</td>
</tr>
<tr>
<td>Snow -17</td>
<td>EBM/TIM</td>
<td>Daily</td>
<td>(T_a, P, C_M, \rho)</td>
<td>[1]</td>
</tr>
<tr>
<td>SWAT</td>
<td>EBM/TIM</td>
<td>Daily/Hourly</td>
<td>EBM: (T_a, P, RH, \varepsilon, R_{in,s})</td>
<td>[6,7]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TIM: (T_a, C_M)</td>
<td></td>
</tr>
<tr>
<td>HEC-1</td>
<td>EBM/TIM</td>
<td>Daily</td>
<td>EBM: (T_a, P, RH, \varepsilon, R_{in,s})</td>
<td>[8]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TIM: (T_a, C_M)</td>
<td></td>
</tr>
<tr>
<td>Urban snowmelt models</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSPF</td>
<td>EBM</td>
<td>Hourly</td>
<td>(T_a, T_d, P, W, C, R_{in,s})</td>
<td>[14]</td>
</tr>
<tr>
<td>USM</td>
<td>EBM</td>
<td>Hourly</td>
<td>(T_a, P, RH, W, \alpha, R_{in,s}, R_{n,s}, SCS)</td>
<td>[15]</td>
</tr>
<tr>
<td>GUHGM</td>
<td>EBM</td>
<td>Daily</td>
<td>(T_a, P, RH, W, \alpha, R_{in,s})</td>
<td>[16]</td>
</tr>
<tr>
<td>SDM</td>
<td>EBM</td>
<td>Hourly</td>
<td>(T_a, P, RH, W, \alpha, R_{in,s}, SCS)</td>
<td>[17-19]</td>
</tr>
<tr>
<td>MU- MOUSE RDII</td>
<td>TIM</td>
<td>Daily</td>
<td>(T_a, P, C_M)</td>
<td>[20]</td>
</tr>
<tr>
<td>EPA SWMM</td>
<td>EBM/TIM</td>
<td>Daily</td>
<td>(T_a, P, C_M, \rho)</td>
<td>[21]</td>
</tr>
</tbody>
</table>

Note. The parameters from snowmelt models are: \(T_a\) is air temperature [°C], \(T_d\) is dew point [°C], \(P\) is precipitation [mm], \(RH\) is relative humidity [%], \(W\) is wind speed [m·s⁻¹], \(\rho\) is snow density [kg·m⁻³], \(\alpha\) is snow albedo[-], \(\varepsilon\) is emissivity of the atmosphere [-], \(R_{in,s}\) is incoming shortwave radiation [W·m⁻²], \(R_{n,s}\) is incoming longwave radiation [W·m⁻²], \(F\) is fractional forest cover[-], \(C\) is fractional cloud cover , \(\varepsilon_s\) is air vapor pressure [hPa], \(SCA\) is snow cover area, \(SCS\) is snow cover shape, \(J\) is Julian day, \(\lambda\) is latitude and \(C_M\) is the snowmelt degree-day coefficient [mm·(degree-day·°C)⁻¹].
4. Discussion and conclusion

For cold regions, the presence of snow plays an important role in the management of the urban hydrological cycle. This study presents an overview of common snowmelt modelling approaches, and discusses key differences between urban and rural snowmelt modelling. A key challenge is the selection of an affordable snowmelt model for heterogeneous urban conditions, from existing model categories TIM, EBM, or hybrid methods. This is based on the availability of input data and on the ability to consider the shape of urban snow covers. This survey findings provide a basis to evaluate and select a suitable model to simulate snowmelt in a specific area. In all the cases where temperature is a good predictor of snowmelt process (e.g. for forested areas), empirical methods (TIM) are preferred because they use readily available input data and they reproduce a large part of the snowpack variations. Even the TIM urban models (MU, EPA SWMM) are the most comprehensive urban models, they can be adapted to specific snow deposit shapes by calibration and by adjustment of melt factors. They use daily time resolution and for better results hourly time steps have to be adopted.

Net radiation is considered a better single predictor of snowmelt than temperature. If radiation data is available, the use of the EBM can improve the accuracy of snowmelt rates and runoff. For heterogeneous urban environments, the application of EBM requires to take into account several characteristics of urban snow: the rate of change of snow albedo, the variation of snow depth and of the snow density based on the snow covers distribution. Also, longwave radiation from buildings and full-sun/shadowed effect affects the fluxes from the surface of snowpack. The net radiation fluxes, observed for all the snow cover types, revealed the shortwave radiation as the dominant radiation flux contributing to snowmelt (with the exception for the snow located near the building walls). As a consequence, the albedo of urban snow is a very important factor in urban snowmelt modelling. The snow albedo decreases faster in the urban areas than in rural areas. Urban snow has a higher net radiation absorption than the rural snow of the same age, so the snowmelt is more intense in the city than in rural environments. This means that the snowmelt in cities begins earlier and proceeds at a higher rate. Even if the impervious surfaces are free from snow during snowmelt, the frozen ground or the presence of snow piles do not allow snowmelt to infiltrate into the ground, so the excess water can easily cause flooding.

TIM has been proven to be valuable in rural areas but does not capture the spatial heterogeneity of urban conditions. EBM can be adapted for each type of snow cover in the urban areas in order to incorporate the different characteristics of the snow. Three major EBM urban models (USM, GUHM and SDM) were developed for research purposes while the remaining EBM were originally developed for non-urban conditions. Due to extreme spatial variability of urban snowpack locations, only the USM and SDM are taking into account the snow cover shape. For example, USM allows seven combinations of snow cover and ground surface types that can result after redistribution. Also snow cover redistribution options included in urban models EPA SWMM, USM and GUHM. From the EBM that require albedo, for natural snow in rural conditions, ESCIMO calculates snow albedo using an ageing curve approach: albedo decreases with the snow age. The urban EBM using as albedo a time-varying input are SDM, USM and GUHM which calculates the albedo over time on the basis of urban conditions. Regarding snow density SNOW-17 calculate changes over time for rural conditions while all the urban EBM are taking in account a constant density of the snowpack. The trend in snowmelt modelling is to implement appropriate model modifications to classical snowmelt models to be potentially applicable to urban snow covers. Thus, TIM needs to define the snowmelt coefficient for each class of the snow cover. EBM needs to estimate or to use simplifying assumptions that are not affecting the accuracy, for all the parameters (albedo, density, changing shapes of snow piles, and etc.).

Acknowledgements

This work is supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CCCI-UEFISCDI, under the framework of the project “Innovations for eXtreme Climatic eventS (INXCES)”, project number 48/2016, within PNCDI III. Particular thanks are given to Johannes de Beer at Geological Survey of Norway for his helpful technical review.
References