Snowdrift formation in forested open drains: field study and modelling patterns

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Nordic Hydrology **Vol 38 No 4–5 pp 425–440** © IWA Publishing 2007

Received 5 December 2006; accepted in revised form 11 July 2007

Abstract The problem of the clogging of open drains by drifting snow has become more significant along with the appearance of tendencies and considerations regarding the rehabilitation of these artificial watercourses by woody vegetation growing on slopes and riparian buffers. Referring to the full-scale field measurements supplemented with the results of hydraulic modelling of drifting snow, conducted to examine the influence of trees and shrubs growing on open drain slopes on the clogging of drains by snowdrift, it was determined that: (1) woody vegetation, influencing the distribution of snow within the riparian zones of the forested drain, contributes to the reduction of snow accumulation in its bed; (2) the clogging extent of forested drains depends on the type of pattern of cross section of woody vegetation strips (on this point there are some considerations presented); (3) it is possible to use hydraulic modelling of drifting snow to forecast some practical issues related with this phenomenon.

Keywords Open drain; snowdrift; woody vegetation

Notation

$B_s \times b_s \times h_s$	trapezium cross-section dimensions
CV	coefficient of variation
d	particle diameter
Fr_Δ	densimetric Froude number
g	gravitational acceleration
H	depth
H_C	height between slope surface and tree crowns
H_{WV}	woody vegetation strip height over upper drain slope edge
I	flow energy gradient
L	linear dimension
$L_f \times h_f \times b_f$	flume dimensions
p	level of significance
R	hydraulic radius
Re	Reynolds number
Re_*	particle Reynolds number
SD	standard deviation
SE	standard error
U_*	bed-shear flow velocity

doi: 10.2166/nh.2007.021

V	flow velocity
Z_0	equivalent surface roughness
α	scale coefficient
ρ	specific density
υ	coefficient of kinematic viscosity

Subscripts

a	air
d	particle
L	linear (geometrical)
n	parameter under natural conditions
m	parameter under modelling conditions
T	time
V	velocity
w	water

Introduction

In latitudes similar to those of Lithuania, the snowy period lasts from 100–160 d and the amount of drifting snow carried by blizzards can reach 100–150 $m^3\,m^{-1}\,yr^{-1}$ (Nyalabzheskiy *et al.* 1972). The wind-drifted snow accumulates in surface depressions, snows up roads, as well as both streams and open drain beds (hereinafter drain(s)), causing drain-clog problems. It was proved that the hydraulic conductivity of open drains clogged with snow decreased significantly, constituting sometimes only 8–15% of that for which it was designed (Smirnov and Litvinyuk 1984; Zakrazhevskiy and Vakhonin 1985). Moreover, a lot of culverts and other hydraulic structures affect the hydrologic situation of snowed-up drains causing both the clogging of sub-surface drainage systems and creating the risk of the structures being washed out. Therefore, it was recommended to sometimes remove clogged snow from snowed-up drains in spring (Zakrazhevskiy and Vakhonin 1985).

The problems associated with the clogging of drains by drifting snow have become even more significant when tendencies and considerations have occurred regarding the possibility of the rehabilitation of regulated streams (present-day drains) by means of the growing of trees and shrubs on slopes and riparian buffers (Kern 1991; Mander 1995; Rimkus *et al.* 2003; Lamsodis *et al.* 2006). This is because woody vegetation reintroduced on banks, despite it being a valuable contribution to technique in stream restoration, can also be an obstacle for the drifting snow when there is a blizzard. However, a review of the literature shows that there is little experimental data concerning the effect of exposed vegetation on wind speed and snow transportation and accumulation in open trenches (Smirnov and Litvinyuk 1984; Kuts 1988). Therefore, the evaluation of the influence of woody vegetation growing on slopes upon the clogging of drains by wind-blown snow is the main objective of this work. To reach a satisfactory outcome, however, we faced some problems. (1) The factors causing snowstorms and snowdrift formation in drain beds are of a stochastic character. These are: the occurrence of snowfall and the presence of snow cover; wind speed and direction; air and snow temperature, and moisture. Actually, meteorological factors are responsible for properties in the snow pack and drifting snow such as snow particle bonding and cohesion, kinetic friction and snow cover surface roughness, particle rebound and expulsion, and that, in turn, as it was shown by Li and Pomeroy (1997) and Pomeroy and Essery (1999), determine the threshold wind speed for snow transport. (2) Directions of various drains and, as often as not the directions of several stretches of the very same drain, are rather different. (3) Only a few of the drains that stretch into open fields exhibit woody vegetation on the slopes (Lamsodis 1999: Rimkus *et al.* 2003). In the meantime, this vegetation does not have the impact of creating a serious fencing effect for drifting snow; moreover, it cannot present the continuous woody vegetation strips with cross-section profiles of different patterns.

The above-listed considerations conditioned that the necessary accumulation of a significant amount of data about snowdrift formation in particular forested drains outdoors was quite complicated and possible only over a longer period of time. To avoid these difficulties, particularly those related to the absence of snow pack and woody vegetation strips of different patterns, and often fluctuating winds, it was decided to introduce methods of physical modelling. These are methods based on the simulation of the movement of particles such as sand (soil) and snow in a wind tunnel and a hydraulic flume. (1) Wind tunnels were adopted and are still successfully used for solving a variety of theoretical and practical problems related to a methodology of simulation, evaluation of properties of drifting particles, boundary layer, wind, etc., and the correlation between them, and the designing of various structures that will be affected by drifting snow, sand or soil (Brier 1972; Iversen 1979; Račinskas and Morkūnaitė 1988; Iversen and Rasmussen 1999; Michaux *et al.* 2002; Cornellis and Gabriels 2003, 2004; Leiti *et al.* 2006). (2) As long ago as 1949 Prandtl had indicated that the movement of dry snow particles in air is similar to the turbulent movement of fine sand particles in water. Later on, the principles and criteria of scaling and the similarity of the model and prototype were worked out (Calkins 1974, 1975; Wuebben 1978; Sharp 1981; Munson *et al.* 2002); it was also shown that the hydraulic modelling of drifting snow was analogous to some models of suspended sediment transport and deposition in river beds.

We chose hydraulic modelling as it was available to us and finely suited to our purposes; i.e. to clarify whether woody vegetation strips on slopes affected the formation of snowdrifts in the drain; if this is so, then what form of patterned cross-section of strip is more acceptable, i.e. that would not increase clogging of the drain.

Methods and materials

Field studies

This field study on the formation of snowdrifts in drains was a part of investigations performed between 1993 and 1996 on the impact of woody vegetation growing on slopes upon the capacity of drains to fulfil their water-receiving and discharging functions.

With reference to the versatility of the data collected, two drains and the winter of 1995/1996 were selected as being the most suitable. The winter was the most abundant in snow over the last two decades (the probability 3%; the snowy period lasted from early December to early April) and a large number of drains were snowed up.

Slopes of one of the drains were overgrown with woody vegetation, the height of which approximated about 5.4 m over the upper edges of slopes, and the density averaged 1.2 stems m^{-2}.

Describing field shelterbelts, Lisenkov (1971) classified them into three categories: thick, openwork and blown-through (Table 1). According to his classification, the shelterbelts growing on slopes of the Pakruostė-4 drain paralleled the openwork one.

Both drains had cross-sections of similar dimensions and arable lands surrounded the stretches where the snow cover was studied (Figure 1). The directions of the stretches were nearly perpendicular. In terms of clogging risk, it made both drains hard to compare together during the same storm. However, (1) this could not essentially influence the run of snowdrift formation processes themselves; (2) due to the long-lasting snowy period and often fluctuating winds, both drains were finally affected by blizzards about equally.

The depth of snow cover was studied in four 100 m long transects which crossed both stretches and were situated 30 m apart. The distances between the test points were 10 and

Table 1 Characteristics of different patterns of cross-section profiles of shelterbelts

	Area of gleam gaps (%)	
Category and characteristics of cross-section profile	**Among stems**	**Within crowns**
Thick: little gleam gaps in the whole profile	0–10	0–10
Openwork: normal amount of gleam gaps in the whole profile	15–55	15–55
Blown-through: many gleam gaps among stems, little within crowns	60–70	0–10

0.5 m in the riparian zones and drain beds, respectively. The testing was done on 22 January, 14 February, 6 March and 20 March. It was found that in open fields the snow depth averaged 28, 32, 45 and 49 cm (standard deviation $SD = 2–4$ cm), respectively.

To define the meteorology of the winter, data from the Dotnuva weather station (located 14 km away) was used.

The whole period (from 1 January to 20 March) was rather cold but not stormy; the daily average air temperatures fluctuated from -0.8 to -21.7°C, and the maximum wind speed ranged from one to nine meters per second.

Modelling methodology

Basic specifications

For turbulent open channel flow the viscous effects are small and consequently strict adherence to the Reynolds number is not required. In our case during the windstorm the Reynolds numbers are large so viscous forces are small in comparison to those forces due to gravity and inertia. In this case Reynolds numbers similarity is not maintained and models are designed on the basis of Froude number similarity. Care must be taken to ensure that the model Reynolds numbers are also large, but they are not required to be equal to those of the prototype. According to Snyder (1972) the similarity in turbulent flow conditions is valid when $Re_m \geq 2 \times 10^4$. For those models with rough surfaces (bushes) similarity the threshold decreased (Sharp 1981).

As the actual wind speed above land surface and water flow velocity under modelled conditions are high enough, viscosity and Coriolis forces are non-essential, and the

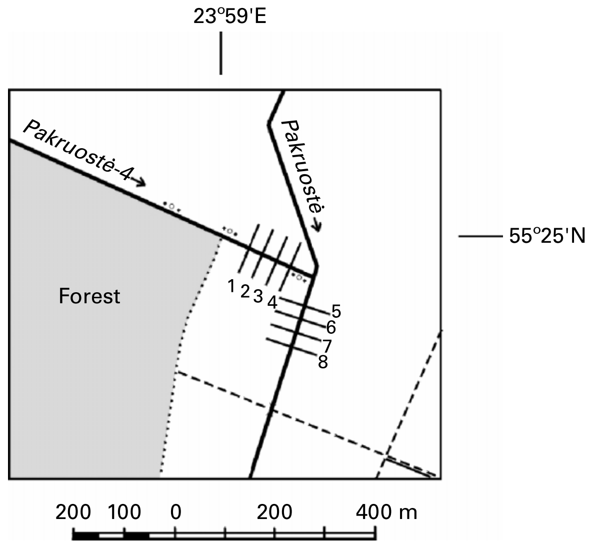

Figure 1 Location of stretches of drains Pakruostė and Pakruostė-4 (with slopes not overgrown and overgrown with woody vegetation, respectively) where snow cover was studied: 1–8: transects of measurement of snow cover depth

modelling can be performed irrespective of the numbers of Rossby (*Ro*) and Reynolds (*Re*). The determinative for these dynamic systems is the densimetric Froude number (Fr_Δ), which estimates the relation of buoyant and inertial forces occurring in media of different density:

$$Fr_\Delta = \frac{V}{\sqrt{g\frac{\Delta\rho}{\rho}H}} \tag{1}$$

where

V – average velocity of flow in current boundary layers;
g – acceleration of gravity;
H – average depth of flow;
ρ – specific density of flowing medium;
$\Delta\rho$ – difference of specific densities of suspended particles and flowing medium.

To have the model similar to the natural system, this modified Froude number is to be equal for both systems, i.e.

$$Fr_{\Delta_m} = Fr_{\Delta_n}. \tag{2}$$

As the atmospheric flows are turbulent and the movement occurs in the sub-zone of rough pipes the equivalent roughness and flow conditions of the modelled surfaces are to be identical, i.e. the condition has to be realised as follows:

$$\left.\begin{aligned}\mathrm{Re}_m &\geq 2\times10^4\\ \mathrm{Re}_{*m} &\geq 2.5\end{aligned}\right\}, \tag{3}$$

where Re_m – Reynolds number of flow;

Re_{*m} – Reynolds number of sediment particles evaluating the roughness of surface elements:

$$\mathrm{Re}_{*m} = \frac{U_* Z_{0m}}{\upsilon}, \tag{4}$$

where Z_{0m} – equivalent value of roughness elements under model conditions;

υ – coefficient of kinematic viscosity;
U_* – bed-shear flow velocity:

$$U_* = \sqrt{gHI} \tag{5}$$

where I – flow energy gradient.

In respect of the above-mentioned equations as well as to the known Jensen criterion (Jensen 1958) (Equation (6)), necessary model scales (geometric, particle, velocity, time) were selected and the identity between the hydraulic model and the snowstorm modelled has been proven:

$$\frac{1}{X} = \frac{L_m}{L_n} = \frac{Z_{0m}}{Z_{0n}} \tag{6}$$

where

$1/X = \alpha_X$ – scale of natural parameter (X) modelled;
L_n and L_m – linear dimensions under natural and modelled conditions;
Z_{0n} – equivalent value of roughness elements under natural conditions.

Data for model scaling

The modelling of snow clogging of drains was carried out in a hydraulic flume with a changeable bed slope and dimensions of 20.00 × 0.75 × 0.50 m ($l_f \times h_f \times b_f$).

Wind speed and direction were modelled by water flow, whilst movement of snow and the formation of snowdrift were modelled on the basis of the movement of fine sand particles in water. It is known that the threshold wind speed for snow transport ranges from 4 to 14 m s^{-1} depending on the extent to which dry or wet, fresh or aged snow is affected by the wind (Li and Pomeroy 1997). (When wind speed reaches 10–20 m s^{-1}, snow particles mostly move along with the air mass in a suspended form).

Other data necessary for the model scaling are presented in Table 2.

Scaling and identity proof

There were some extra constraints that had to be considered when scaling. (1) Dimensions of the hydraulic flume available. Considering this, the geometric model scale $\alpha_L = 0.1$ was

Table 2 Data necessary to scale the model and prove the model identity with the natural snowstorm

Parameter	Value	Comments
Drain modelled:		
cross-section shape;	Trapezium	
cross-section dimensions ($B_{sn} \times b_{sn} \times h_{sn}$), m	7.0 × 1.0 × 2.0	Adopted referring to actual drains
Woody vegetation:		
height of strips over upper edges of slopes (H_{WVn}), m;	2.0	Adopted as actually possible case
space height between drain slope and crowns (H_{Cn}), m	0.8	Adopted as actually possible case
Snow cover:		
depth (h_{dn}), m;	0.4	Adopted as actually possible case
equivalent roughness of snow-covered grassy field (Z_{0n}), m;	0.023	Sharp (1981) referring to Isyumov
size of dry drifting snow particle (d_n), m;	0,0001–0.0004	Sharp (1981) referring to Isyumov; Smirnov and Litvinyuk (1984)
Specific density of snow particles (ρ_{dn}), kg m^{-3}	170–250	
Wind characteristics:		
wind speed modelled (V_n), m s^{-1};	16.0	Adopted referring to the above-text
threshold wind speed for dry snow (V_{dn}), m s^{-1};	8.0	Li *et al.* (1997)
specific density of air (ρ_a), kg m^{-3}	1.0	
Sand used in model:		
average size of particles ($d_{50} \equiv d_m$), m;	0.00012	Selected sand characteristic
specific density (ρ_{dm}), kg m^{-3}	2650	Selected sand characteristic
Water and flow characteristics:		
threshold flow velocity for sand particles (V_{dm}), m s^{-1};	0.31	Calculated referring to Levi (1948) and the above data[1]
specific density (ρ_w), kg m^{-3};	1000	
coefficient of kinematic viscosity (ρ_w), m^2s	0.000001	

[1] $V_{dm} = 1.4\sqrt{gd}\,\ln\frac{H}{7d}$; calculated when water depth in the flume $H_m = 0.5$ m

adopted. (2) Size of snow particles. As dry drifting snow particles are too fine, it is impossible to arrange for the particles used in the model to be geometrically identical to the actual ones. If this identity was established, the flow around such small particles (compared with snow particles they are 10 time smaller in our case) would not be turbulent. Considering this, it is necessary that the size of particles simulating the snow particles in a hydraulic flume be enlarged. As a result, the action of viscosity forces would then be reduced as well.

Having adopted the geometric scale of the model and using Equation (6), the equivalent value of roughness under model conditions has been assessed: $Z_{0m} = \alpha_L Z_{0n} = 0.1 \times 0.023 = 0.0023\,\mathrm{m}$. The subsequent modelling results showed that the height of sand ripples occurring in the flume ensured the roughness of its bottom comparable with the equivalent calculated one.

Referring to the above-mentioned, the model parameter scales were assessed and the identity between the model and natural conditions verified (Table 3).

Model parameter values

The model of the drain was made from wood planks and set across (perpendicularly to the axis of the flume) the bottom of the flume in such a way that the upper edges of both slopes of the drain model coincided with the flume bottom covered with sand, of the same grain-size composition as the one used for snow modelling.

Trees and shrubs on the slopes of the drain model were simulated with nails and iron cuttings (Vasilchenko 1985). For modelling the openwork and blown-through patterns of woody vegetation strips growing separately on the lee, windward and also on both slopes was adopted. To simulate the required amount of gleam gaps between stems and branches, the appropriate amount of iron cuttings and nails was installed (Figure 2).

All the parameters of the model are listed in Table 4.

The operation of the snowstorm modelling would be started along with the introduction of sand sediments at the beginning of the flume when the required flow velocity would be consistent; the modelling would last until the sand clogging of the drain model ceased.

Table 3 The parameter scales and identity proof of the hydraulic model used for the modelling of snow drifting in drains

Scale; identity conditions	Value	Comments
Geometric (α_L)	0.1	Adopted
Particle size (α_d)	1.2	Calculated using Equation (6) and data presented in Table 2[1]
Velocity (α_V)	0.031	Calculated using Equations (2) and (1) and data presented in Table 2[2]
Time (α_T)	3.2	Calculated as ratio of α_L and α_V
$Fr_{\Delta m} = Fr_{\Delta n}$	$0.12 = 012$	Calculated using Equations (2) and (1) and data presented in Table 2[2]
Particle, $Re_{*m} \geq 2.5$	$713 > 2.5$	Calculated using Equations (4) and (5) and the above-presented data[3]
Flow, $Re_m \geq 2{\times}10^4$	$61000 > 20000$	Calculated using Equation (4)

[1] $\alpha_d = \dfrac{d_m}{d_n}$

[2] $\dfrac{V_n}{\sqrt{g\frac{\Delta\rho_n}{\rho_a}H_n}} = \dfrac{V_m}{\sqrt{g\frac{\Delta\rho_m}{\rho_w}H_m}};\ \dfrac{V_m}{V_n} = \sqrt{\dfrac{\Delta\rho_m\rho_a H_m}{\rho_w\Delta\rho_m H_n}};\ \Delta\rho_n = \rho_{dn} - \rho_a;\ \Delta\rho_m = \rho_{dm} - \rho_w;\ \dfrac{H_m}{H_n} = \alpha_L;\ \dfrac{V_m}{V_n} = \alpha_V$

[3] Calculated when $V_m = V_{dm} = 0.31\,\mathrm{ms}^{-1}$; when $V_m = V_n \times a_V = 0.5\,\mathrm{ms}^{-1}$. $Re_m = 100000$

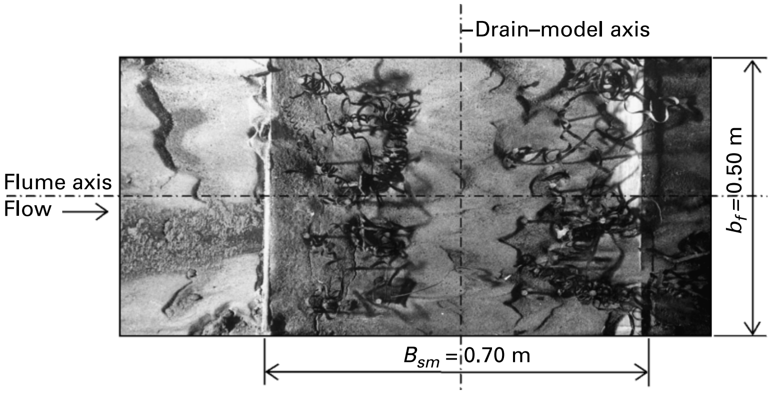

Figure 2 View of plan projection of hydraulic flume with clogged drain model by sand after one of the modelling stages was completed. The dark twists seen are the iron cuttings that simulated woody vegetation on the slopes

Results

Field studies

In respect of the probability of the studied drain stretches being clogged by wind-blown snow, the most dangerous wind bearings were: (1) for the Pakruostė drain: E, ESE, SE (from ESE side) and W, WNW, NW (from WNW side); (2) the Pakruostė-4 drain: N, NNE, NE (from NNE side) and S, SSW, SW (from SSW side). However, it will be observed that the nearness of the forest could: (1) weaken the winds blowing from the W and affect the snowdrift formation in the Pakruostė drain from WNW side and (2) deflect to the N the winds blowing from the SE, thus enhancing snowdrift formation in the Pakruostė-4 drain from its SSW side.

Although the winter was not stormy, wind-blown snow accumulated in drain beds forming the drifts on lee slopes. The snowdrift grew over time and in the case of the

Table 4 List of all the parameters of the model used

Parameter	Value	Comments
Drain model:		
simulating material;	Wood planks	*v.* the text above
cross-section shape;	Trapezium	*v.* Table 2
dimensions ($B_{sm} \times b_{sm} \times h_{sm}$), m	0.70 × 0.10 × 0.20	Tables 2, 3: ($B_{sn} \times b_{sn} \times h_{sn}$) α_L
Woody vegetation strip model:		
simulating material;	Nails, iron cuttings	*v.* the text above
height (H_{WVm}) m;	0.20	Tables 1 and 2: H_{WVn} α_L
height of space between slope and crowns (H_{Cm}), m;	0.08	Table 2: H_{Cn} α_L
stem density (gleam gaps among stems), %;	5.0–40.0	Table 1; depends on category
branch density (gleam gaps within crowns), %	30.0–40.0	Table 1
Snow cover and drifting snow particles model:		
simulating material;	Sand	*v.* the text above
cover depth (h_{dm}), m;	0.04	Tables 2 and 3: h_{dn} α_L
roughness of sand cover ripples (Z_{0m}), m;	0. 0023	*v.* the text above
size of sand particles (d_{dm}), m	0.00012	*v.* Table 2
Air mass movement (wind) model:		
simulating medium;	Water	*v.* the text above
flow velocity (V_m), m s^{-1}	0.50	Tables 2 and 3: V_n α_V
threshold flow velocity for sand particles (V_{dm}), m s^{-1}	0.31[1)]	*v.* Table 2

[1] This value of flow velocity corresponds to the wind speed of about nine metres per second

Pakruostė drain finally occupied the whole cross section (the drain had no woody vegetation on the slopes) (Figure 3(A)).

In the Pakruostė-4 drain (its slopes were overgrown with woody vegetation), the formation of snowdrifts occurred on both slopes (Figures 3(B) and 4). This might have happened because there was no fence impeding the wind in large spaces on both sides of the drain, and the snow-stormy winds were able to blow from either side of the drain. Thus the role of woody vegetation remained somewhat indefinite. Maybe this vegetation contributed to the preservation of an unclogged central part of the drain cross section. However, there was no direct evidence to prove this assumption except for the fact that the overgrown drain was nevertheless not entirely clogged. Here it will be observed that approaching the overgrown drain, the snow depth in the riparian zones tended to increase, i.e. the nearer the drain, the deeper the snow pack to be measured (Table 5). Naturally, this additionally accumulated amount of snow takes no further role in the process of the clogging of the drain, and could not be explained otherwise as a result of a suppressing effect of woody vegetation on the slope acting as a fence for drifting snow. At the end of the snowy period (on 20 March), over 1.9 m^3 of additional snow was remaining in the riparian zones, 50 m wide and 1 m in length around the drain. If the excess of snow accumulated in the drifts on the slopes over the hypothetical horizontal plains, whose elevation corresponded to the snow cover

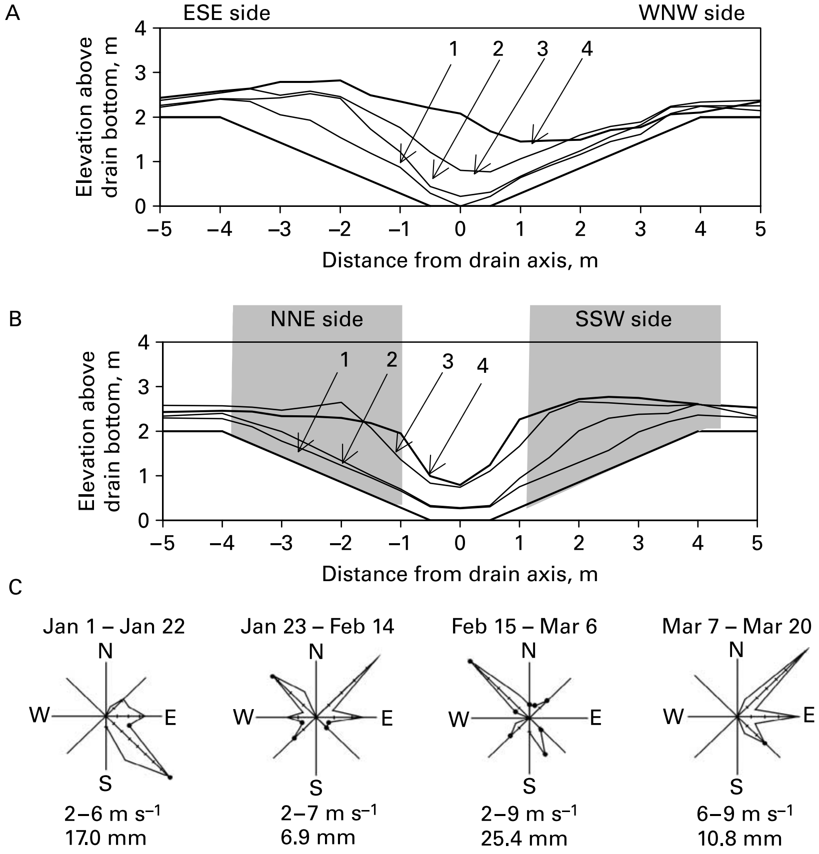

Figure 3 Snowdrift profiles formed in 1996 in the drains Pakruostė (A) and Pakruostė-4 (B) (non-overgrown and overgrown with woody vegetation, respectively): 1–4: profiles measured on 22 January, 14 February, 6 March and 20 March. The grey fields mark the approximate spaces, which were occupied by trees and shrubs. (C) Brief meteorology of the period: windrose (value of graduation equals 5%, the dots mark the bearings when it was snowing); below: maximum wind speed occurring during snowfall (m s^{-1}) and precipitation (mm)

Figure 4 Snowdrifts formed in the Pakruostė-4 drain on 20 March 1996. The strips of woody vegetation on slopes resembled those in the openwork category: width of both strips approximated 3.0–3.5 m; height of trees averaged 5.4 m over the upper edges of the slopes; average stem density was 1.2 stems m^{-2}

surface elevation in the fields 50 m apart from the drain, was added to the above-mentioned additional amount of snow kept back in the riparian zones, the total amount over this plain would approximate to 2.5 m^3 m^{-1} (Table 6). Interestingly, this amount of snow was only a little less than the volume of part of the cross section of the Pakruostė-4 drain (2.9 m^3 m^{-1}), which had then been kept free of snow below the above-mentioned hypothetical plain. It appears that if there had been no woody vegetation on the slopes, this additional amount of snow would have totally clogged the drain.

Modelling results

When there was no strip of woody vegetation simulated on the drain-model slopes, the horizontal whirlpools occurred in the drain-model bed causing both the deposition of sand particles and forming sand drifts on the upstream slope, whilst the particles from the downstream slope were washed away. In the case when the process was rather protracted the whole bed profile of the drain model was clogged by sand drift (Figure 5). Naturally, the changes in flow direction, velocity or the interruption of modelling process run would result in any of the intermediate forms of the drift.

Table 5 Snow cover depth (h_s ± *SE*, cm) in the riparian zones of the Pakruostė-4 drain. $CV = 0.05-0.27$; *SE* – standard error

		Distance from the slope edge, m							
Date	**Drain side**	**1**	**2**	**7**	**17**	**27**	**37**	**50**	**Level of significance (p)[1]**
January 22	NNE	30 ± 1	32 ± 1	32 ± 0	31 ± 0	31 ± 0	31 ± 0	31 ± 1	
February 14	NNE	36 ± 2	36 ± 2	36 ± 2	34 ± 1	34 ± 1	34 ± 1	33 ± 1	
March 06	NNE	57 ± 2	53 ± 2	50 ± 2	46 ± 2	46 ± 2	44 ± 2	43 ± 1	0.01; 0.001
March 20	NNE	47 ± 2	48 ± 2	50 ± 1	49 ± 1	47 ± 2	45 ± 2	44 ± 2	
January 22	SSW	30 ± 2	27 ± 1	25 ± 1	26 ± 1	26 ± 1	27 ± 1	27 ± 1	0.05; 0.1
February 14	SSW	38 ± 3	32 ± 2	30 ± 2	28 ± 1	28 ± 1	30 ± 1	30 ± 1	0.01; 0.05
March 06	SSW	56 ± 2	49 ± 2	47 ± 2	46 ± 1	46 ± 1	47 ± 1	47 ± 2	0.001; 0.01
March 20	SSW	55 ± 2	50 ± 2	50 ± 2	52 ± 4	54 ± 4	54 ± 4	52 ± 4	

[1] Level of significance of differences between the snow cover depth tested at the distance of 1 and 27, and 1 and 50 m from the drain

Table 6 Additional amount of snow preserved in the riparian zones of 50 m width and on forested slopes of drain Pakruostė-4 over the hypothetical plains, corresponding with snow surfaces on the open field at the end of the snowy period

	Snow depth in field, m		**Amount of snow over hypothetic plain corresponding to snow surface in field, $m^3\ m^{-1}$**			
Date	**NNE side of drain**	**SSW side of drain**	**Riparian zones[1]**	**Drain slopes**	**Total**	**Cross-section area free of snow, m^2**
March 6	0.43	0.47	1.72	0.81	2.52	3.39
March 20	0.44	0.52	1.94	0.52	2.46	2.90

[1] Width of one riparian zone = 50 m

It will be observed that, due to the turbulence resulting in the suspended flow of sand particles in the flume, sediment formed dunes on the bottom. This corresponded to the natural length of snowdrift waves of 20–30 m. Moreover, on the top of the sand dunes, ripples of 0.005–0.015 m height and 0.05–0.15 m length occurred. As a result, the precise roughness for the model surface has been ensured. (Incidentally, the scaled-up ripples were equivalent to the ones occurring on a snow cover surface during a blizzard.) The dunes and ripples would appear every time whether the overgrown or not overgrown drain were being modelled.

The strips of nails and iron cuttings on drain-model slopes simulating the growth of woody vegetation created an additional resistance to water flow. Running up against the strip of cuttings that simulated an openwork strip on the lee slope (upstream in the model), the flow virtually split into two currents. The upper one over-circumvented the strip, resulting in whirlpools beyond, whilst the lower one slowed down, causing the discharge and deposition of suspended sand particles on the flume bottom; some before the drain model and on its upstream slope. It should be noted that the velocity of this current would decrease even more due to its expansion in the cross section when water entered the drain-model bed. For the similar reason, the water velocity of the upper one would also decrease due to the expanding cross-section of the upper current after it passed over the strip model. The decreasing water velocity forced further deposition of suspended sand particles despite the above-mentioned whirlpools beyond the strip impeding sand drift growth in the drain-model bed. These whirlpools caused localised shallow depressions when the growth of sand drift would finally cease (Figure 6(B)).

When the openwork strips were modelled on the windward (downstream in the model) and on both slopes, the sand particles clogged the cross section of the drain model almost as much (Figures 6(B, C)). Although all three attained shapes of sand drift cross section were different, the above-mentioned indications of the flow impact on sand drift formation can be

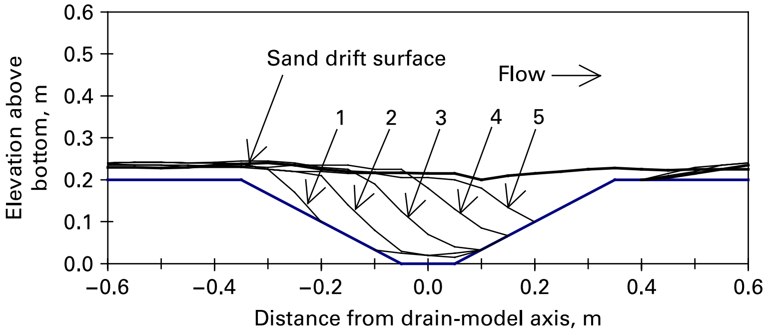

Figure 5 Sand drift formed in the drain model with no strips on the slopes after modelling of snowstorm in the hydraulic flume was completed: 1–5: the drift profiles successively measured during the process

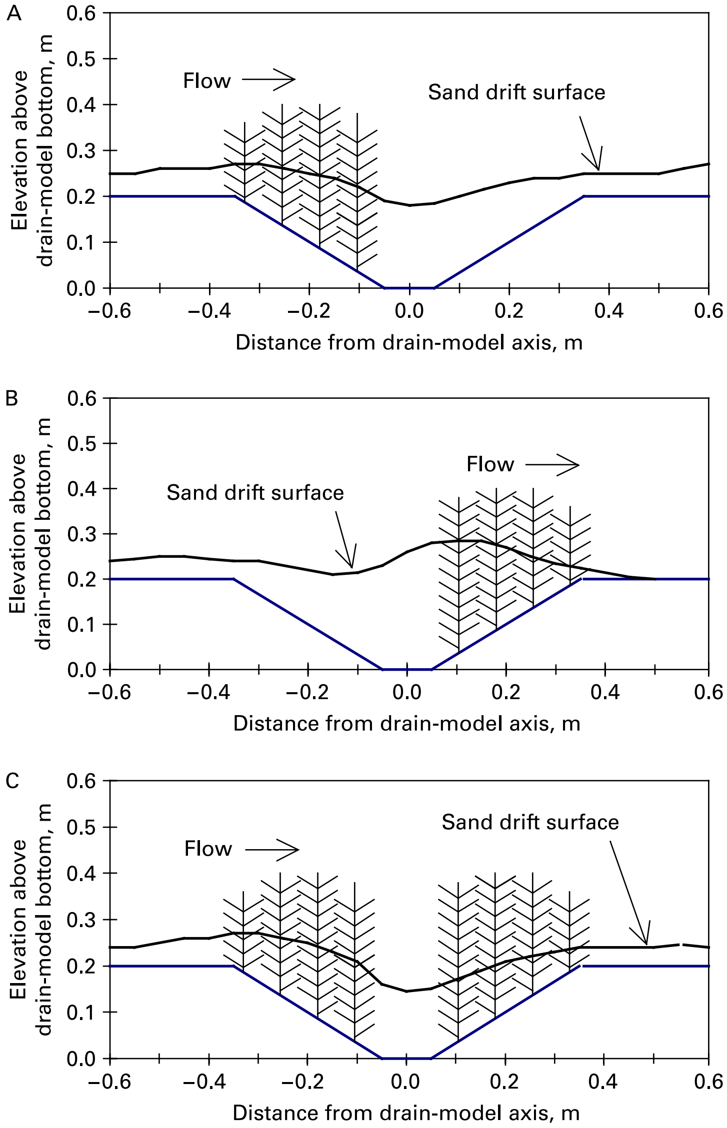

Figure 6 Sand drifts formed in the drain model with the openwork strips on upstream (A), downstream (B) and both (C) slopes after the modelling of snowstorm in the hydraulic flume was completed. The modelling lasted until the drifting of sand ceased, i.e. about 2.0–2.5 h, depending on the pattern modelled. The herring bone-like icons mark cross sections of strips arranged using nails and iron cuttings

distinguished, i.e. (1) some deeper drifts before the strips were caused by the decrease in flow velocity and (2) certain depressions on the sand's surface occurred just beyond the strips, where the whirlpools originated.

The process of drifting was different when the blown-through strips were modelled. These strips had comparatively free space between the crowns and the slope surface (between the drain-model slope and the iron cuttings of the strip model), i.e. the way for the lower current to cross the strip model remaining herewith strong enough to carry suspended sand particles, thus preventing their deposition on the drain-model slopes. Therefore, when those strips on the upstream slope and both slopes were modelled, only an insignificant amount of sand was able to become accumulated exclusively on the bottom (Figures. 7(A, C)).

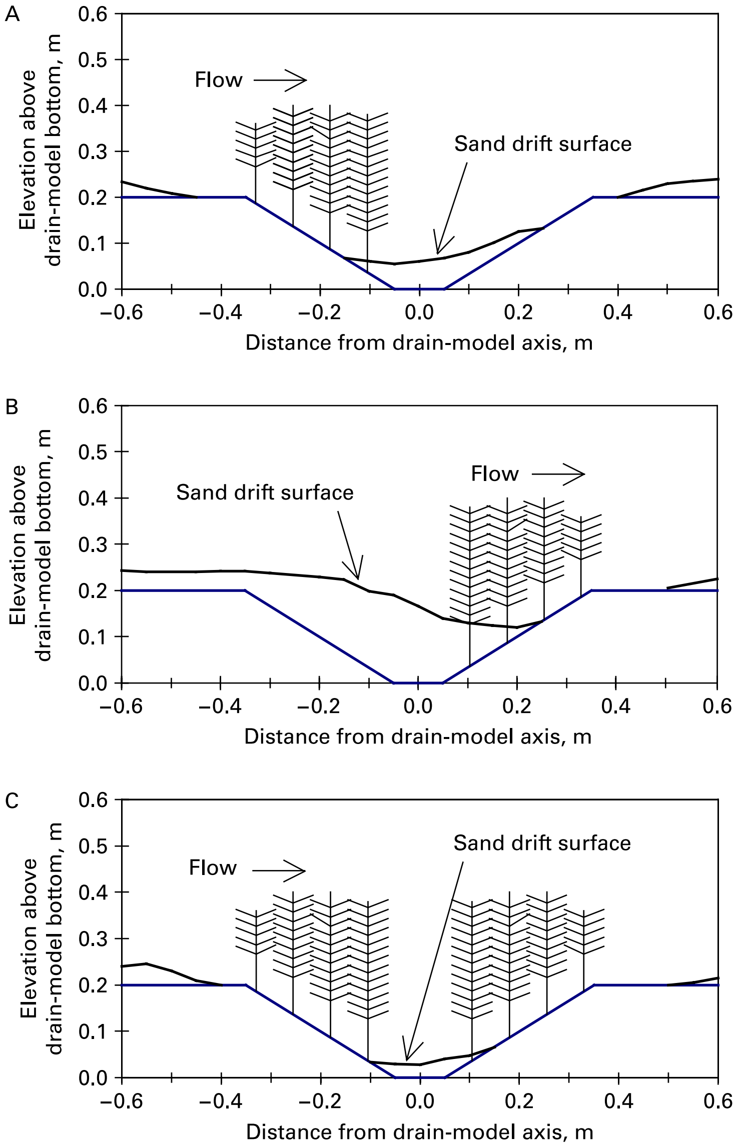

Figure 7 Sand drifts formed in the drain-model with the blown-through strips on upstream (A), downstream (B) and both (C) slopes after modelling of snowstorm in hydraulic flume was completed. The modelling lasted until the drifting of sand ceased, i.e. about one hour (the (A) and (C) cases) and 2.0–2.5 (the (B) case). The herringbone-like icons mark cross sections of strips arranged using nails and iron cuttings

In contrast, the bed of the drain model was almost fully clogged up when the blown-through strip on the downstream slope was modelled (Figure 7(B)). It happened because the empty drain-model bed and the strip beyond it (on the downstream slope) together created conditions for the flow velocity to decrease, and the whirlpools to originate within and over the drain-model bed space.

Discussions

Drains in open fields act as the sinks (particular barriers for drifting snow), trapping drifting snow masses. Snowdrifts usually clog drains every time when there are snowy conditions in winter. Snowdrifts would originate at the upper edge of the slope and would grow approaching the drain axis. (Due to fluctuation of winds, the snowdrifts were able to occur and progress on both slopes.) When the snow would not choke up the drain totally, the snowdrift would always end in a rather steep slope. In such cases, the depth of the snow pack in that part of the cross section of the drain not choked up was about equal to the depth of the snow pack in adjacent fields. The field measurements and modelling results validated the above.

Although shelter belts appear as serious obstacles to drifting snow, causing its accumulation within the belts and their environs (Kopanev 1953; Lisenkov 1971), the process of clogging of drains proceeded likewise, irrespective of whether drain slopes exhibited woody vegetation or not. Only the partially clogged central part of the cross section of the drain when slopes were forested, as well as the greater amount of snow accumulated in the riparian zones, revealed a certain protective effect of woody vegetation strips against the clogging of drains. Moreover, referring to Konstantinov and Struzer (1965) and Lisenkov (1971), it will be expected that, if trees and shrubs on drain slopes entered a net of green plantation, the more even and deep snow cover would occur on fields within the meshes of such a net, due to the decrease in wind speed and turbulence. This would result in the lesser threat of forested drains being snowed up.

However, there was no exact correlation of field study results with the results of modelling. The drain model with openwork strips on both slopes was usually clogged with sand near to the top; this had occurred because the strong wind ($16\,\mathrm{m\ s^{-1}}$) blowing perpendicularly towards the drain and continuous snow cover was modelled, and the process lasted a rather long period of time, i.e. for several hours. If such extreme conditions really occurred, this would result in the total clogging of the actual drain dimension. However, in the winter of the years 1995–1996 the weather conditions differed substantially from the above-mentioned extreme conditions, i.e. the wind speed never exceeded nine metres per second, and the wind direction seldom was perpendicular to the direction of the drain.

On the other hand, some quantitative differences between the field study and modelling results once more show that the processes concerning drifting snow are complicated: either they run according to natural conditions or they are simulated in the flume. The complication of natural conditions is determined by the stochastic character of the processes, with a very unique combination of features causing the blizzard and influencing its progress. These conditions are exclusively meteorological, and therefore cannot be controlled.

However, it will be observed that: (1) the problems of sediment bed-load measurements and precise hydraulic modelling still exist as well. This is often due to the non-homogeneous nature of turbulent flow and suspended particle interaction near the bottom layer (Muste 2002; Toorman 2003; Nezu and Azuma 2004). This results in differences of flow fluctuation between the model and prototype velocity distribution fields. The geometry of tree stems and branches as roughness elements can, in addition, distort the local turbulent flow velocity distribution; (2) the density ratio between sand particles and water is about 10^2 times smaller than the density ratio between snow particles and air. The same applies for drifting particles of quartz where it is known to influence the relative importance of transport modes (Iversen and Rasmussen 1999). Thus, in air fluxes saltation is dominating over bed load whereas in water it is less important. This is the main reason why the problem of fulfillment of initial and boundary conditions in drifting snow modelling is complicated.

Nevertheless, the dynamic equilibrium of fully rough turbulent flows resulting in similar densimetric Froude numbers for different fluids overflowing local obstacles can create correspondingly similar regimes and sediment transport conditions (Grishanin 1974; Wang 1986; Chanson 1999). As a consequence, the motion of snowdrifts is occurring in a similar manner to sand dune movement in the water bodies (Prandtl 1949). Therefore, although both processes were similar, the difficulties in fulfillment of initial and boundary conditions could also make the results of the modelling somewhat divergent.

Compared to any other strip modelled, the blown-through strips arranged on both slopes protected the drain bed more from being drifted. It was proposed to extend the width of the strips of trees by some metres in the riparian zones. The space between crowns and ground surface formed in the whole strip width with respect to the inclination angle of the drain slopes creates additional pressure in the lower current. Strengthened bed-load current has higher transporting capacity and is able to better carry suspended particles, protecting the bed from being choked up with snow (Rimkus and Vaikasas 2003). It will be observed that, over time, woody vegetation density on drain slopes tended to decrease due to natural competition between plants for available light, with some not surviving (Lamsodis 1999b), together with the fall of lower dead tree branches As a result, an alteration can be expected in the pattern of the woody vegetation strip from the openwork into blown-through. In time therefore, the threat of clogging of forested drains would have to decrease as well.

Conclusions

Slope woody vegetation strips affect the snow distribution in riparian zones and reduce the snow mass that gets into the drain bed if arranged on the lee or on both slopes. With respect to the reduction of the clogging of drains or any other trench beds by snowdrifts, the blown-through strips showed themselves to be most effective.

It is possible to model in a hydraulic flume the clogging of drains and any other trenches by snow, forecasting practical issues related to drifting snow. The quantitative adequacy of the modelling results related to the process of the natural phenomenon depends on the accuracy of the initial and boundary conditions in the model prototype.

Acknowledgements

The authors thank Mr. Gary Willis for his help with editing the manuscript and two reviewers for valuable comments.

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