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EVALUATIONS OF RESERVOIR STORAGE LOSS DUE TO GROUNDED ICE DURING WINTER OPERATION

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During winter operation of northern reservoirs, part of a reservoir's water may become immobilized in the form of ice grounded on embankments. The volume of grounded ice and the rate of deposition of ice is examined for three reservoirs: Gouin (Saint-Maurice River, Quebec, Canada) and Outardes 4 (Aux Outardes River, Quebec, Canada) and La Forge 1 (La Forge River, La Grande Complex, Quebec, Canada). Results show that the ratio of the volume of immobilized water to that of the active storage varies from 2% to 8% for the Gouin reservoir, from 0.4% to 1.15% for the Outardes 4 reservoir, and around 20% for the La Forge 1 reservoir. The rate at which the volume of immobilized ice grows during the early and mid winter is compared to inflow and outflow rates of the reservoirs.

Keywords: Ice cover, artificial neural networks, lake, growth, storage.

1. Introduction

During the winter operation of some Canadian reservoirs, a fraction of the water volume that is accounted for with the reservoir's nominal storage curve is in fact unavailable because it is immobilized in the form of ice deposited on the reservoir's embankments. The process of ice deposition on the banks of reservoirs banks is illustrated in Figure 1.. Some of these reservoirs are presently used to accumulate water during the spring, summer and fall in order to sustain hydroelectric production during winter. During winter, the discharge of unregulated streams is at its lowest while the need for electric power is at its highest. The level of these reservoirs is thus progressively lowered and water is made available for production further downstream.

The immobilization of water through the grounding of ice was examined in a previous paper by Seidou et al [2006.2] and is reviewed here briefly. The previous paper presented evaluations of the volume of grounded ice for two Quebec reservoirs : Gouin and Outardes 4. The same method is applied here to the La Forge 1 reservoir and the results are further discussed.

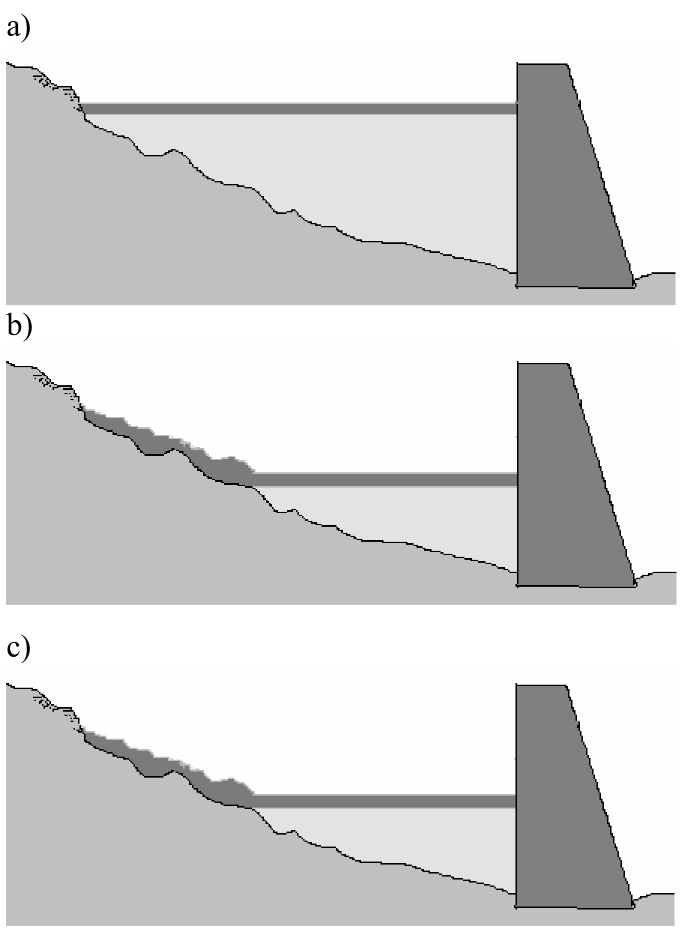

Figure 1: Ice deposition on the banks of the reservoir: early winter; b) middle of the winter; c) end of winter.

Methodology

The evaluation of storage immobilization have been evaluated with two models. The first one is a model of the growth of ice thickness in the early and middle part of winter as a function of weather only. The second one is a model of the rate of grounding of the ice cover as a function of time as a function of the reservoir's water level and its storage curve. Combining these models allows one to produce time series of total grounded ice volumes, and of the rate of grounding. These are then compared to the reservoir's available storage for operations, and to characteristic values of volume flow of water at the inlets, outlets and unregulated local basin.

The lake ice growth model

The ice growth model is the regional Artificial Neural Networks (ANN) model developed in Seidou et al. [2006.1]. The model fits ice thickness measurements at 26 monitored lakes, and predicts ice thickness during the growth period either at the same locations for dates without measurements (local ANN models), or at any ungauged site in the region (regional ANN model), provided that the required meteorological input variables are available.

The input variables are the average (in time) daily rainfall during the ice-growth period, and the sum of solar radiations during the period of ice-growth. The output variable is the growth rate of the square of the ice thickness ${H_I}^2/D_d$. The model architecture is illustrated in Figure 2. Once a time series of the growth rate of the square of the ice thickness is obtained, a time series of ice thickness can easily be reconstructed.

The model was calibrated and validated using a) ice thickness measurements from 26 lakes spread throughout Canada, b) daily meteorological data (temperature, rainfall, snow on the ground) from the national weather stations network, and c) incident solar radiation at the top of the atmosphere which was computed as a function of time and the geographic location of studied sites.

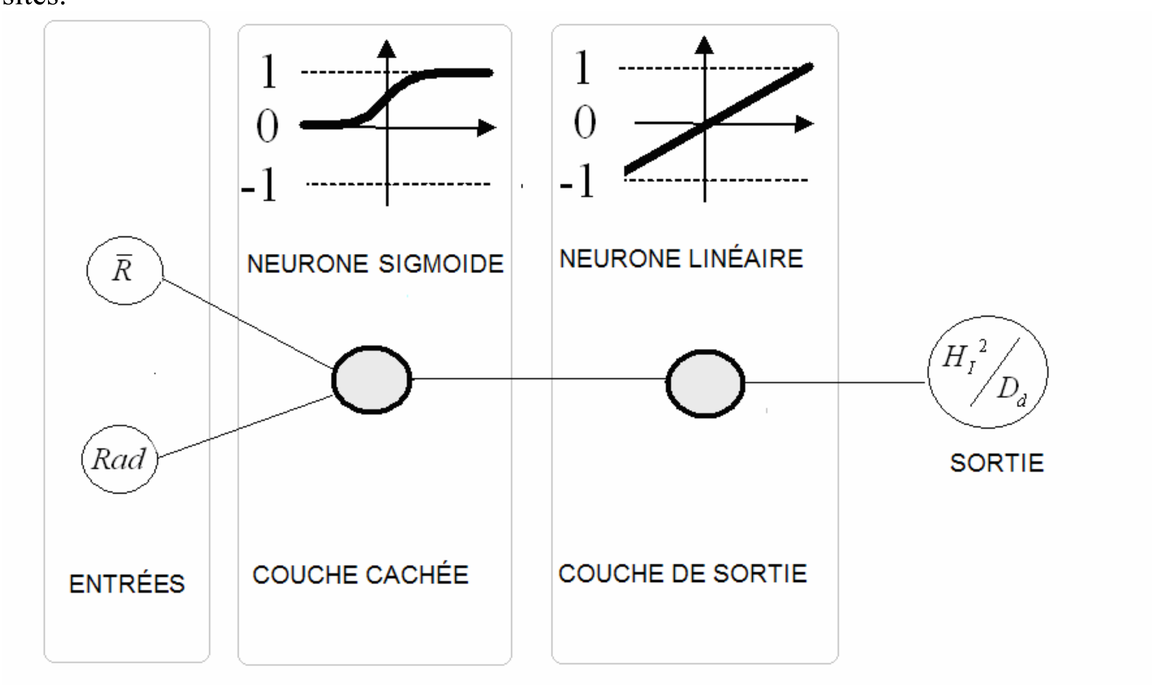

Figure 2: Architecture of the global ANN ice growth model.

The global ANN model displayed an *rmse* of 18.15 cm for a mean ice depth ranging from 66 to 290 cm. *Seidou et al.* [2006] also showed that ANN models compare well with those of the deterministic physics-driven Canadian Lake Ice Model CLIMO [*Menard et al.* 2002a, 2002b; *Duguay et al.*, 2003] in terms of root mean square error (*rmse*) and in terms of relative root mean square errors (*rrmse*). Their predictions were also slightly more precise than those obtained with a revised version of Stefan's Law (*RSL*). The global ANN model was thus used to simulate lake ice thickness in the remainder of the study.

The immobilized storage model

In the simple ice grounding model presented in the previous paper by Seidou *et al*. [2006.2], the rate of deposition of floating ice on the banks of a reservoir during winter operation is viewed as the sum of two simultaneous processes. The first process is described by neglecting changes in the water level; a part of the ice cover progressively becomes attached to the bottom as the ice thickens during winter because the inferior face of the ice cover reaches the bottom in shallow areas. The second process is described by considering that, as the water level goes down, some ice will get deposited on the banks. Ice advected into the reservoir by rivers is ignored. The precipitation of snow on the ice cover is also neglected. The ice cover is seen as a floating slab of uniform thickness at a given time.

Expression [1] is derived from volume conservation arguments involving the storage curve of the reservoir:

$$V_G(t+\Delta t) - V_G(t) = \left(S(Y_B(t+\Delta t)) - S(Y_B(t))\right)\cdot\frac{H_I(t+\Delta t)+H_I(t)}{2} \qquad [1]$$

where t is time, $V_G(t)$ is the volume of ice that is grounded and immobilized, $H_I(t)$ is the thickness of the ice slab, $Y_B(t)$ be the elevation of the bottom side of the floating ice slab, $S(z)$ be the storage area of the reservoir as a function of altitude z. Given that $Y_S(t)$ is the water level's altitude as a function of time, which is a familiar and well measured quantity for reservoir operators, one can evaluate $Y_B(t)$ with the following expression : $Y_B(t) = Y_S(t) - H_I(t)$

Given the two time series $Y_S(t)$ and $H_I(t)$ and the reservoir storage relationship $S(z)$, relationship (1) allows the evaluation of the volume of grounded ice $V_G(t)$ with respect to time through simple integration. Relationship (1) is defined in the context of a downward trend in $Y_B(t)$ although Seidou et al [2006.2] argue that short episodes of upward evolution should not have a deleterious effect on the calculation.

The volume of grounded ice $V_G(t)$ starts with a null value just before freeze up and grows from there until the conditions for the validity of the integration are no longer met, such as the arrival of the freshet or the melting of the ice cover.

Case studies for the estimation of the volume of grounded ice

The calculation of the volume of ice left on the banks was made on two hydro-Quebec reservoirs: the Gouin reservoir located at the head of the Saint-Maurice River (Quebec, Canada) and the Outardes 4 reservoir (Aux Outardes River, Quebec, Canada). Figure 3 illustrates the location of the two reservoirs. The purpose of the Gouin reservoir is the regulation of the rate of discharge of the upper reaches of the river in accordance with a variety of interests, including a number of hydroelectric installations located downstream. It is considered fairly large (1570 km^2) and much ramified. The winter pattern for the Gouin water level is a general downwards trend because of the combination of low flow from the hydrologic basin and large releases due to

high demand for hydroelectric power. The difference between the highest level and the lowest level of the reservoir during a given year is relatively low. However, more than 40% of the surface that is immerged when the reservoir is full is uncovered the level lowers. The Outardes 4 reservoir is 652 km2 large and displays a similar pattern during the winter. The fluctuations of the reservoir level are much higher than at the Gouin reservoir, but only a smaller percentage (6.75 %) of the surface emerges at low waters. It is thus expected that the phenomenon of ice deposition be more important at Gouin than at Outardes 4.
The storage area curves of the two reservoirs and the time series of their winter water level were obtained from Hydro-Quebec data banks. The time series of ice thickness had to be computed since no systematic measurement of this variable was available. Thus, the global ANN model described above was used to provide the time series of ice thickness. Since the reservoirs cannot be considered as single points, a sensitivity analysis was first performed to have an estimate of the spatial variability of ice growth on each reservoir. This analysis will also helps choosing the number of points on the reservoirs where ice growth should be simulated.

Results and discussion

Volume of ice grounded on the banks

The Gouin reservoir

The volume of frozen water grounded on the banks at the Gouin reservoir was computed using equation [10] for winters 85-86 to 95-96 and winter 97-98. Winters former to 85-96 were not studied because the historical weather data included in the database were from 1985 to 2002. Other winters between 1985 and 2002 were not treated because of the lack of one or several input data at the nearby meteorological stations. The mean simulated ice thickness, the volume of ice grounded on the banks, the head loss due to grounded ice as well as the ratio of the volume water left as ice on the bank to the volume of water available in the reservoir are presented as functions of time in figure 4. The maximum volume of ice left on the banks varies between 292 million cubic meters of ice (268 millions cubic meters of water) for winter 93-94 and 126 million cubic meters of ice (116 million cubic meters of water) for winter 85-86. The deposit of ice on the banks leads to a drop of 9 to 24 cm of the water level and the volume of frozen water reaches each winter between 3% and 8% of the active storage. These results are summarized in Table 1.

The Outardes 4 reservoir

The volume of frozen water grounded on the banks at this reservoir was computed for winters 85-86 à 97-98 for the Outardes 4 reservoir. The mean simulated ice thicknesses, the volume of ice grounded on the banks, the head loss due to grounded ice as well as the ratio of the volume of water left as ice on the bank to the volume of water available in the reservoir are presented as functions of time in figure 5. The volume of deposited ice varies from 19.17 million m3 (17.57 millions m^3 of Water) for Winter 90-91 to 34.62 million m3 (31.74 millions m^3 of water) for Winter 88-89. The corresponding head loss varies from 4 cm to 8 cm, corresponding to 0.41% and 1.15% of the active storage. These results are summarized in Table 2.

The La Forge 1 reservoir

The La Forge 1 reservoir was chosen for this examination because previous work on Gouin and Outardes 4 showed that the relative importance of the grounding of ice increases when the

reservoir's storage curve is shallow and shows large changes with water level changes of about one meter, which is a rough estimate of the thickness of the fully formed ice cover.
Preliminary estimates show that up to 25 % of the liquid storage of LA-1 in winter is in fact immobilized as grounded ice. The rate of ice grounding reaches peaks of 200 to 250 m³/s and represents up to 25 % of the water withdrawal, and is many times higher than rough estimates of the unregulated water inflow during winter.
During the presentation, more details and diagrams will illustrate this situation.

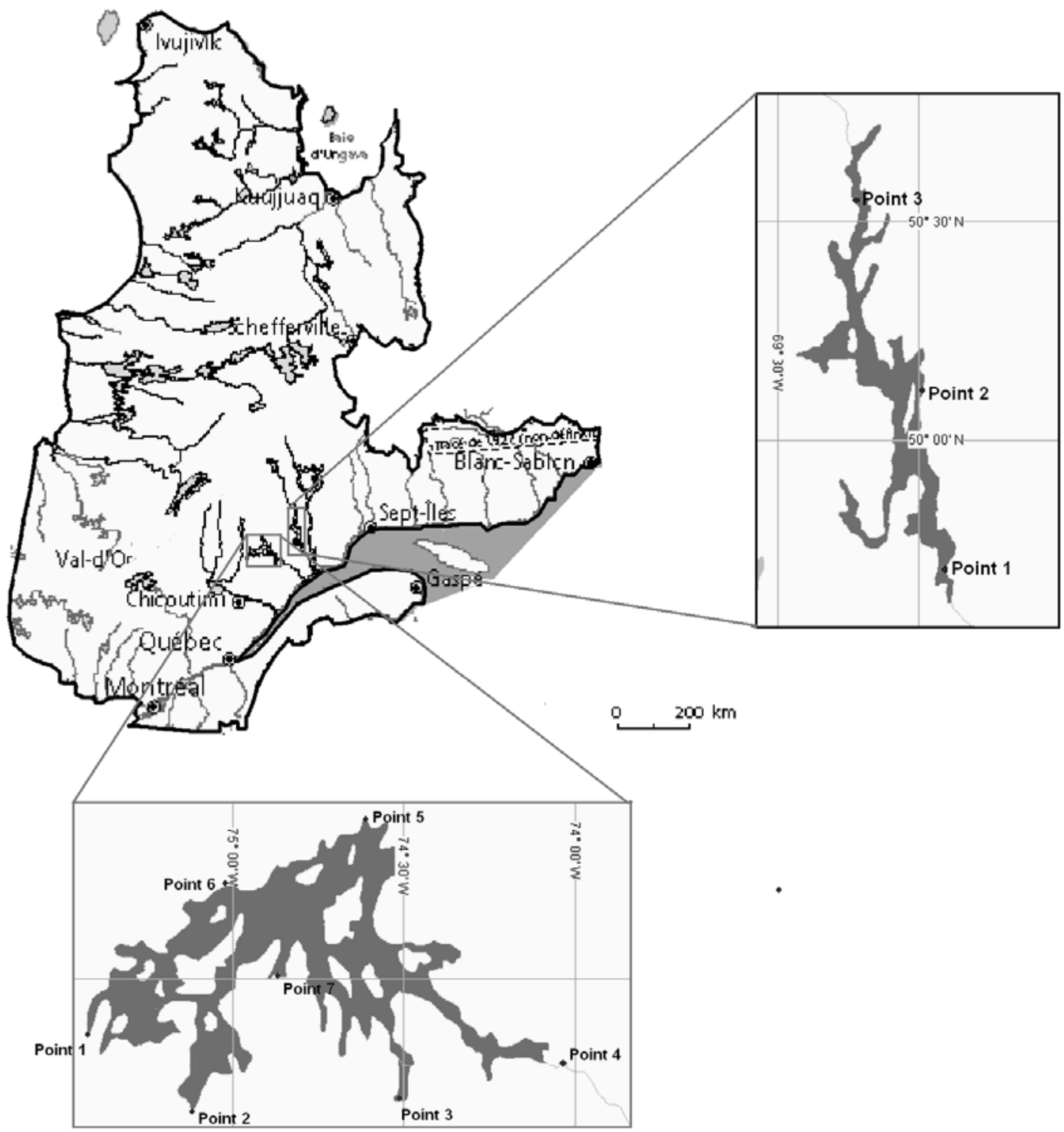

Figure 3: Location of ice growth simulation points at the Gouin and Outardes 4 reservoirs

Table 1: Maximum head loss (max ΔYs), maximum volume of ice left on the banks (max V_G), minimum active storage (min Vol), maximum ratio of the volume of water left as ice on the banks to the active storage (max R) and minimum reservoir level (min Ys) per winter at the Gouin reservoir

Winter	max ΔYs (cm)	max V_G (millions of m^3)	min Vol (millions of m^3)	max R	min Ys (m)
85-86	10	126.80	4313.65	0.03	402.40
86-87	14	190.89	4964.15	0.04	402.94
87-88	24	180.24	2126.12	0.08	399.88
88-89	18	210.17	4048.00	0.05	402.16
89-90	18	185.70	3513.62	0.05	401.63
90-91	9	128.22	5057.55	0.02	403.01
91-92	20	205.39	3513.62	0.05	401.63
92-93	16	218.60	4817.64	0.04	402.82
93-94	22	292.27	4752.90	0.06	402.77
94-95	10	144.29	5176.01	0.03	403.10
95-96	22	190.50	2888.97	0.06	400.91
96-97	11	143.93	4618.58	0.03	402.66

Table 2: Maximum head loss (max ΔYs), maximum volume of ice left on the banks (max V_G), minimum active storage (min Vol), maximum ratio of the volume of water left as ice on the banks to the active storage (max R) and minimum reservoir level (min Ys) per winter at the Outardes 4 reservoir

Winter	max ΔYs (cm)	max V_G (millions of m^3)	min Vol (millions of m^3)	max R	min Ys (m)
85-86	6	25.57	4622.18	0.0055	343.98
86-87	5	21.83	4016.59	0.0054	342.67
87-88	5	21.72	3720.74	0.0058	342.03
88-89	8	34.62	3022.69	0.0115	340.52
89-90	4	19.34	3189.11	0.0061	340.88
90-91	4	19.17	4714.64	0.0041	344.18
91-92	6	25.73	3582.05	0.0072	341.73
93-94	7	31.40	5250.88	0.0060	345.34
94-95	5	23.64	5394.19	0.0044	345.65
95-96	6	27.25	4686.90	0.0058	344.12
96-97	6	25.54	4330.94	0.0059	343.35
97-98	4	19.64	4062.82	0.0048	342.77

Relative importance of the phenomenon

The phenomenon of ice deposition is thus very variable from one reservoir to another. The reason for which ice deposition is so important at the Gouin reservoir is that the reservoir is operated on an annual basis. The reservoir is almost emptied every year, so an important portion of the lake surface (41%) is above the reservoir level at the end of the winter. Ice deposition on the banks is also susceptible to become important when the reservoir is not very deep, or when the slope of the storage curve is low. Ice deposition is much less important at the Outardes 4 reservoir despite a higher variation of the water level, because of steeper reservoir slopes. The surface affected by ice deposition is much smaller than the one at the Gouin reservoir. Ice deposition can be important in a natural lake especially when it represents a storage feeding a river system during the low flow winter period. However, such case is not presented since the principles are the same as in the two case studies. Another situation where ice deposition can be important in natural systems is when the water is not very deep. In this case, an important part of the water can be frozen in the winter, and released during the spring melt.

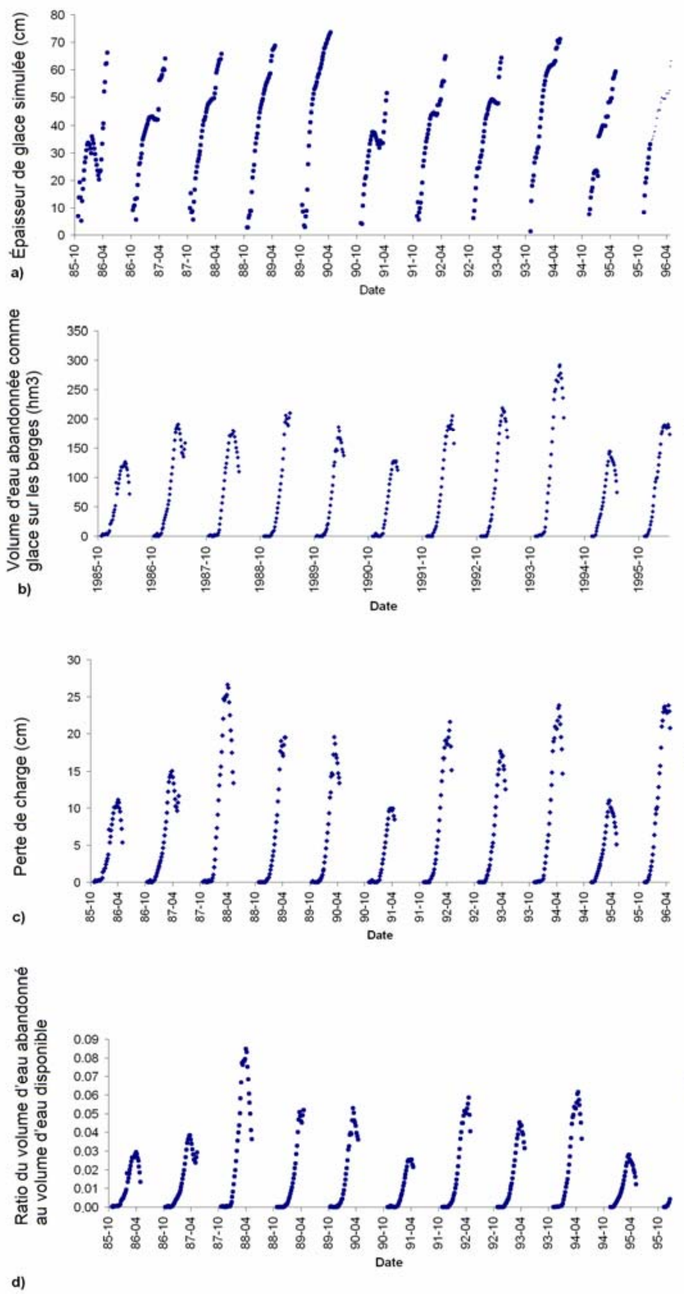

Figure 4: Computation of water volume immobilized by freezing on the banks at the Gouin reservoir: a) simulated ice thickness; b) volume of water left as ice on the banks; c) reservoir level reduction;d) ratio of the volume of water left as ice on the banks to the volume of water available for hydroelectric production.

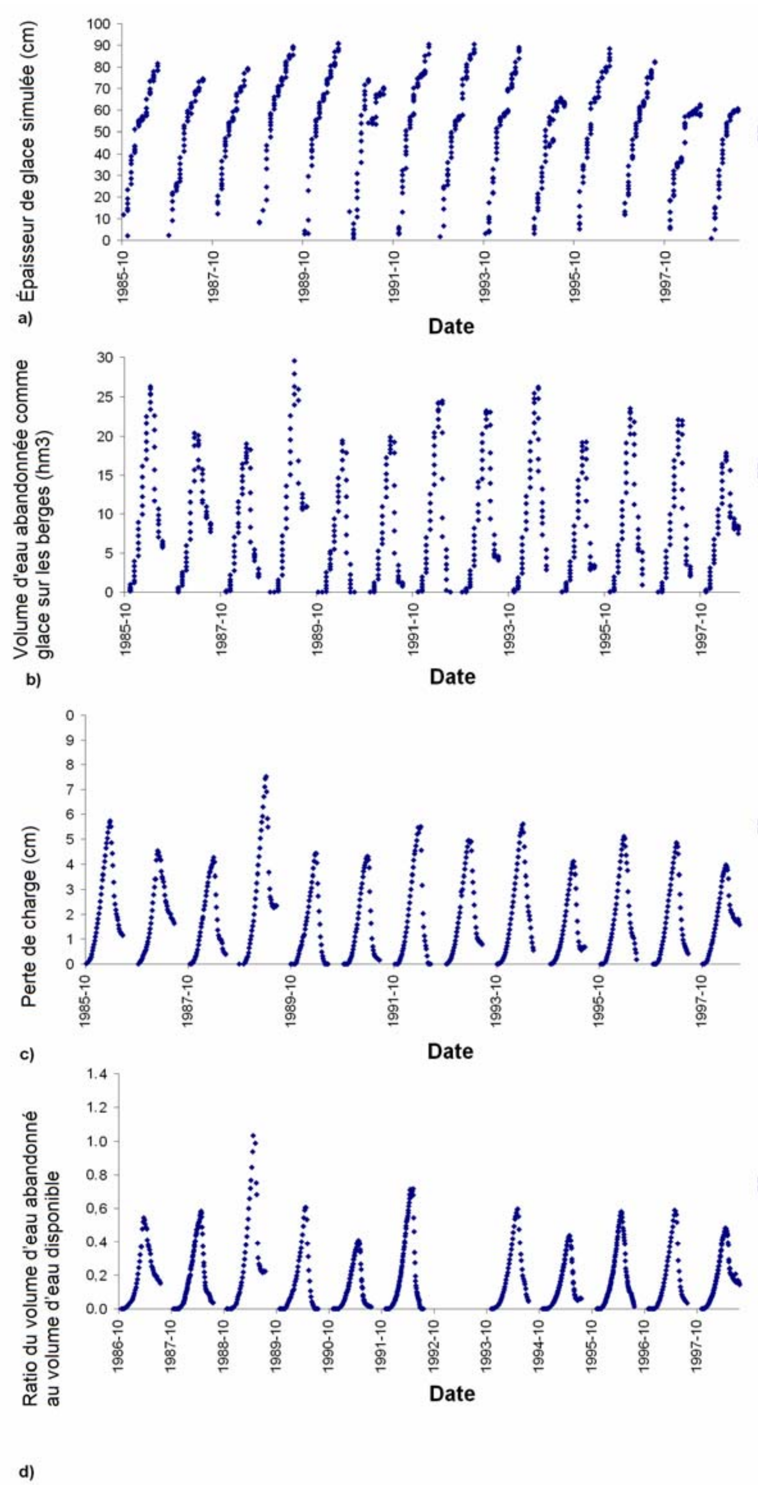

Figure 5: Computation of water volume immobilized by freezing on the banks at the Outardes 4 reservoir: a) simulated ice thickness; b) volume of water left as ice on the banks; c) reservoir level reduction; d) ratio of the volume of water left as ice on the banks to the volume of water available for hydroelectric production.

It must be pointed out that this amount of water is an additional loss to the dead pool storage. Hence, current methods of scheduling reservoir operations (which ignore the phenomenon of ice deposition) overestimate power generation potential during the winter period. Since the importance of ice deposition varies from one winter to another depending of weather and reservoir operations, it is not possible to establish a unique winter storage curve. A real time computation of available storage using the methodology presented in this paper is more practical. The immobilization of water as grounded ice has several negative impacts on hydroelectric production:

1) Part of the storage volume is made unavailable during winter when the demand for electricity is high. Since grounded ice is stocked above the reservoir level, hydroelectric head is lowered. The volume of grounded ice has the same effect as an additional dead pool storage;

2) The immobilized water becomes available at the end of the winter when streamflows are large due to snowmelt, and demand for electricity is low. Therefore, it increases flood threat and the probability of spilling. The marginal value of water is then almost null;

3) The availability of this additional volume of water during the flood season leads to larger design of hydraulic structures, and hence an additional cost of construction.

This phenomenon changes the effective storage curve during the winter. Since it is not currently accounted for in dam operations planning, it may lead to suboptimal decisions.

Conclusions

This paper highlighted the problem of ice deposition on reservoir's embankments during winter operation, and its potential negative impacts on reservoir operations. A methodology is presented to compute the volume of water frozen on the reservoir banks that is made unavailable for hydropower production. ANNs were used in this paper to build a lake ice growth model and to evaluate the amount of water immobilized by freezing during the winter period in the Gouin and Outardes 4 reservoirs (Quebec, Canada). The immobilized portion of the reserve was found to be negligible at Outardes 4, but to represent up to 8% of the amount of water available for hydroelectric production at the Gouin reservoir. Grounded ice acts thus as an additional and unaccounted for dead storage, makes water unavailable when it is more needed and releases it at the end of winter when its marginal value is almost null. Grounded ice can also lead to the design of larger and costlier structures.

Further development of the ice growth model is desirable to hold account of neglected but potentially important border ice formation factors such as snow drift, seiche or wind pressure.

Acknowledgements

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List of symbols

A_I	Area of floating ice slab
D_d	Sum of degree-day
H_I	Ice Thickness

S	Reservoir surface
Rad	Sum of solar radiations on the top of atmosphere
V_G	Volume of grounded ice
V_I	Volume ice that is floating as a slab
V_{TOTAL}	Total volume of ice
Y_B	Bottom elevation of the floating ice slab
Y_S	Surface elevation of water in the reservoir

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