A physical model study of a horizontal riverbed filtration system design for the Montmorency River, Quebec, Canada

Cintia Racine, René Lefebvre, Richard Martel, Claudio Paniconi
Institut National de la Recherche Scientifique – Eau, Terre et Environnement (INRS-ETE),
Université du Québec, Québec, QC

ABSTRACT
A series of physical model experiments in a 1,5 m^3 sandbox were conducted to evaluate the performance of a horizontal riverbed filtration system being conceived for installation in the Montmorency River alluvial sediments to provide drinking water. The proposed water intake is intended for winter operation and should meet a water demand of 70 000 m^3/d. The sandbox model was fitted with a half-conduit of 45 cm length and 15 cm width and was filled with 1,5 m of sifted alluvial sediments (315 µm < diameter < 14 mm). It was instrumented with pressure transmitters and a flowmeter. The flow experiments consisted of drainage sequences with turbid water until complete clogging at the surface, followed by backwash operations. The flow rates achieved in this laboratory setup, when scaled up to the dimensions of the proposed horizontal riverbed filtration system, predict a potential capacity of 391 000 m^3/d. The results of the sandbox experiments are being used to fine tune various aspects of the river system design, such as the optimal grain size of the filtering media, and to provide insights on operational features, such as the minimum required backwash pump capacity.

RÉSUMÉ
Un modèle physique en bac de sable de 1,5 m^3 a été réalisé afin d'évaluer la performance d'un concept de prise d'eau horizontale sous-fluviale implantée dans les sédiments de la rivière Montmorency pour l'approvisionnement en eau potable. Le système de captage sera opéré en hiver et devra répondre à une demande de 70 000 m^3/j. Le modèle physique en bac de sable instrumenté de capteurs de pression et de débitmètre représente la géométrie et l'écoulement d'une demi-conduite de 15 cm de largeur et de 45 cm de longueur. La demi-conduite a été recouverte de 1,5 m d'alluvions tamisés (315 µm < diamètre < 14 mm). À la suite d'un développement adéquat du milieu poreux, des séquences de drainage avec une eau turbide jusqu'à l'atteinte d'un colmatage complet de la surface du lit filtrant et des opérations de rétrolavage ont été réalisées. Ces essais ont permis d'une part d'évaluer le débit de captage nominal du système pleine grandeur sans colmatage qui serait de 391 000 m^3/j. D'autres parts les résultats et les observations réalisés lors de ces essais permettront de raffiner certains aspects du design, tels la granulométrie du matériel filtrant mis en place dans la tranchée de captage et la capacité de la pompe de rétrolavage, et d'établir des stratégies d'opération en drainage et en rétrolavage d'un tel système.

1. INTRODUCTION

Horizontal riverbed filtration systems represent an attractive alternative to conventional water supply systems. Their vicinity to an open water body allows large flow rates to be achieved, while passage through a porous medium allows natural filtering and dilution to occur, producing water of good quality *(Kawecki, 2000; Ray et al., 2002; Birch et al., 2004; Racine et al., 2005)*. The objectives of this study are to validate design and operation parameters of a proposed horizontal riverbed filtration system for a suburb of Quebec City, to investigate clogging processes during drainage, and to evaluate the potential capacity of the operational design. The study uses a physical model in a 1,5 m^3 laboratory sandbox that is based on the geometry, sediment properties, and water flow conditions of the target horizontal riverbed filtration system.

2. METHODOLOGY

2.1 Characteristics of the proposed horizontal riverbed filtration system

The preliminary design for the Montmorency River installation near Quebec City contains 8 horizontal conduits of 30 cm diameter and 75 m length spaced 2 m apart and oriented parallel to the flow of the river. The conduits are to be placed at a depth of 1.5 m within the riverbed sediments, which will have been excavated and sifted prior to installation of the conduits. The sifting procedure will allow removal of the finest (diameter < 315 µm) and coarsest (> 14 mm) particles. The proposed filtration system is intended for winter operation and should meet a water demand of 70 000 m^3/d. Winter water levels in the river at the proposed site are about 0.3 m. The system is gravity driven.

2.2 Sandbox design

The laboratory sandbox was designed to represent 3D flow conditions under drainage and backwash configurations in a filtered media of 1.5 m depth consisting of sifted alluvial sediments excavated from the Montmorency River. Figure 1 shows the relationship between the sandbox and riverbed filtration system flow patterns and geometry. Figure 2 presents the sandbox design and instrumentation. The right boundary of the sandbox in the figure, where the half-conduit is affixed, contains a Plexiglas window spanning the entire height of the sediment column, allowing direct observation of the drainage and backwash experiments.

2.3 Experimental procedures

After filling the sandbox with sifted alluvial sediments, the porous medium was developed by short drainage and backwash sequences to enhance the system capacity. The porous medium development procedure induced a natural sorting of sediments, with gravel and coarse sands dominant in the bottom 160 cm and medium and fine sands dominant from 160 cm to the top of the sand column at 210 cm.

A first drainage test with clear water was conducted to derive the hydraulic parameters of the sifted alluvial sediments and to evaluate the reference capacity of the system (prior to any clogging). After this first test, several drainage and backwash sequences were performed, using turbid water during the drainage portions. The turbidity levels were at least twice as high as found in the Montmorency River under winter conditions. These sediment concentration levels were selected so as to accelerate the clogging process. The changes in the porous media induced by clogging and the consequent losses in system capacity (reduction of flow rate at the conduit outlet) were observed and measured for all tests.

The turbid water was produced by mixing fine particles (diameter < 80 µm) sifted from Montmorency River sediments with aqueduct water at the laboratory. A concentrate was initially produced by agitating the fine particles in a 2000 l water tank, according to the desired concentration. The concentrate was then injected and mixed in a second 2000 l water tank to obtain the desired concentration for the sandbox drainage tests (Figure 2).

The drainage phases were of approximately 24 hours duration to attain complete clogging of the surface layer of the sandbox. When clogging took longer to occur, the turbidity of the water flowing to the sandbox was significantly increased.

Backwash phases with clear water to remove fine particles were initiated when clogging induced a loss of capacity of more than two-thirds the initial capacity. Backwash pulses of 15 minutes duration were used, with flow rates per unit of filter surface area of 0.002, 0.003, 0.004, 0.0055, and 0.006 $m^3/s/m^2$. After each backwash operation, the surface of the sandbox was scraped to remove any fine particles that resettled on the surface. This step is intended to mimic the action of a river current in washing away fine particles after backwashing is performed on a riverbed filtration system.

2.4 Sandbox instrumentation

In order to monitor the clogging process during drainage and the backwash operations, pressure heads, flow rates, and sediment concentrations (turbidity) were recorded during the experiments. Pressure was measured both continuously (with pressure transmitters logged in a CR10X Campbell Scientific datalogger) and manually (at various times, and in particular immediately following the backwash cycles, just before surface scraping).

Figure 2 shows the points where pressure data was collected manually and continuously, with two sensors at each of eight elevation levels along both side walls of the sandbox. The continuous recordings are at the red points in Figure 2, at elevation levels 45, 85, 137.5, 190, and 200 cm. On the right wall, the pressure transmitters at elevation level 45 cm measure the pressure into the half-conduit.

Water flow rates at the outlet of the conduit (during drainage cycles) and at the entry (during backwash cycles) were measured continuously with a flowmeter. Turbidity was measured manually with a table turbidity meter. During drainage phases, water turbidity was measured in both agitation tanks and in the water above the sandbox. During backwash phases turbidity was measured in the overflow water and in the backwash tank shown in Figure 2.

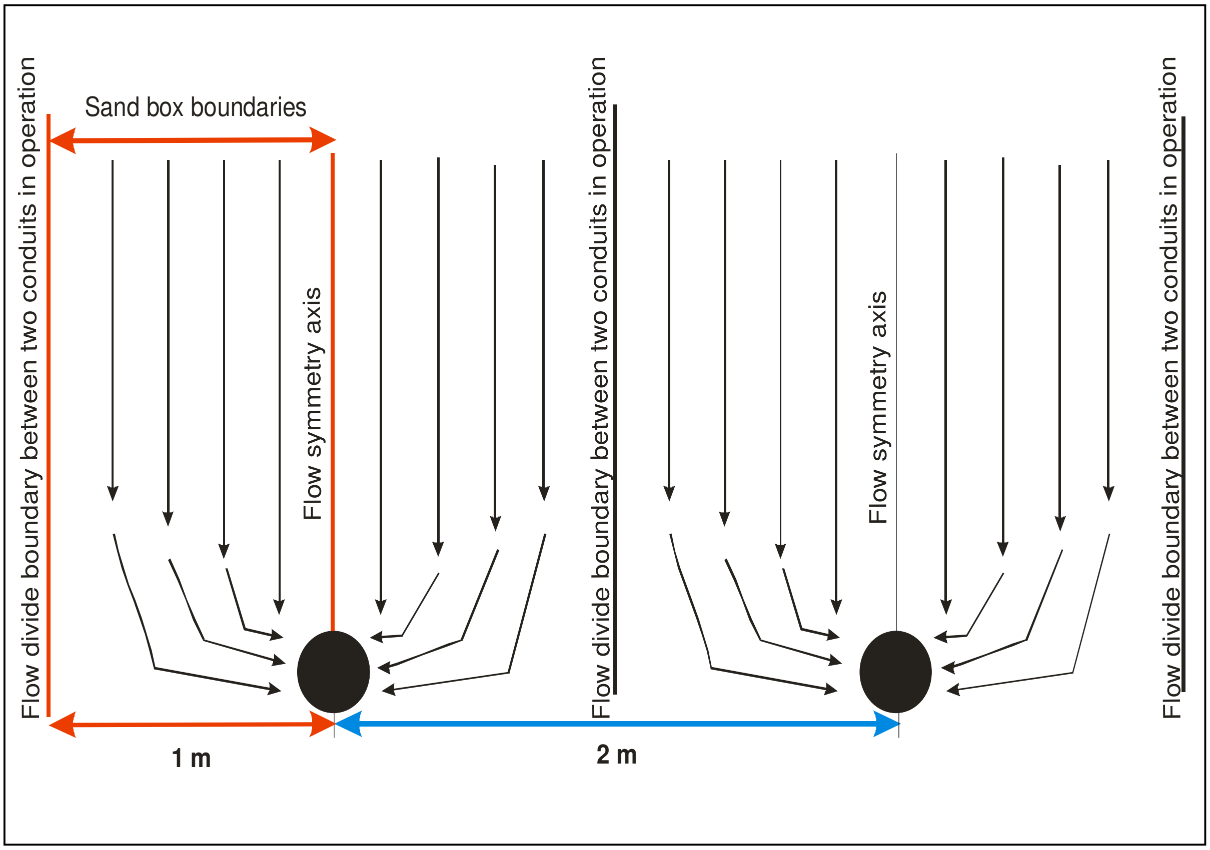

Figure 1: Relationship between the laboratory sandbox setup (red boundaries) and the proposed horizontal riverbed filtration system.

3. RESULTS AND INTERPRETATION

3.1 Drainage test with clear water – Reference system capacity

During the drainage test with clear water, the outlet flow rate per unit surface area was measured at 13.6 $m^3/h/m^2$. This flow rate scaled up to the proposed horizontal riverbed filtration system geometry with a total drainage area of 1200 m^2 (8 conduits of 75 m length, each with capture zone of 2 m – see Figure 1) yields an estimated operational flow rate of 391 000 m^3/d. This value is more than five times greater than the design requirement of 70 000 m^3/d. In this calculation the following assumptions were made: negligible flow interference between conduits; all 8 conduits perform equally, including the two at the edges of the system; the screened conduit used in the sandbox and those proposed for the river have the same performance characteristics per cross section of conduit.

3.2 Drainage and backwash tests

Six sequences of drainage with turbid water and seven backwash operations were conducted. The results of these tests are summarized in Table 1. For each sequence, the results associated with the backwash operation are presented before those of drainage run because the net effect of backwashing on the porous medium is observed in the results of the following drainage test. In Table 1, the results reported for the backwash operation are the backwash flow rates and the effective backwash durations, i.e., when the removal of fine particles from the sandbox was completed or stabilized (as interpreted from the backwash breakthrough curves). The results reported for the drainage cycles following a backwash operation are the behavior of the hydraulic head profiles on the conduit side of the sandbox, the drainage flow rates and their profile trends, the drainage durations, and the water volumes drained.

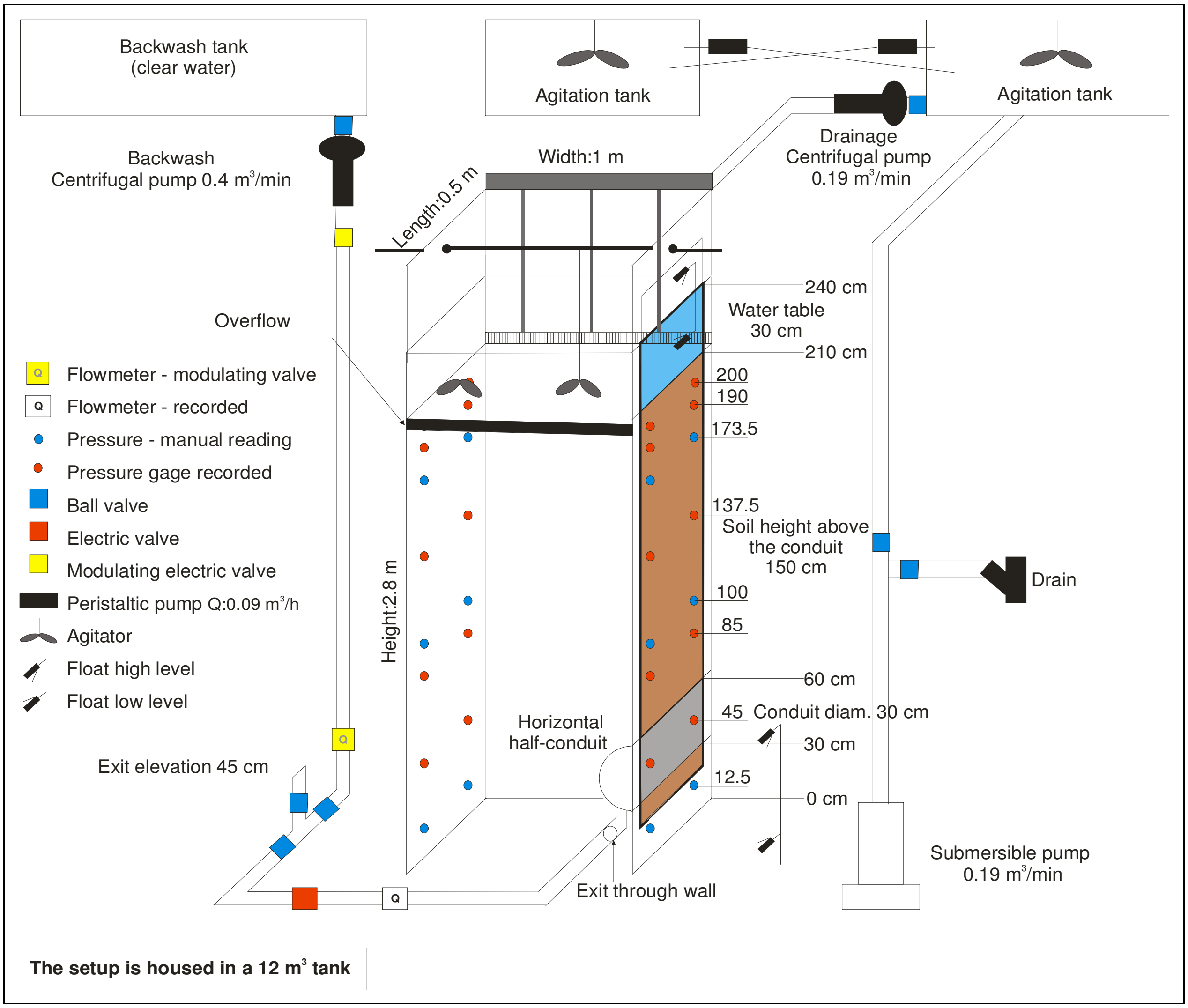

Figure 2: Sandbox design.

Table 1: Summary of sandbox drainage and backwash experiment results

SEQUENCE (DATES; 2008)	BACKWASH		DRAINAGE			
	Flow rate $m^3/s/m^2$ ($m^3/h/m^2$)	Effective duration min	Hydraulic head profile after backwash and before surface scraping	Flow rate and profile trend $m^3/h/m^2$ (Reference flow rate: 13.6 $m^3/h/m^2$)	Total duration h	Drained volume m^3/m^2
1 (5-8 Dec)	0.0020 (6.8)	8	Clogging at the surface	13.0, Decreasing	26.5	316
2 (8-9 Dec)	0.0030 (11.3)	10	Clogging at the surface	12.3, Decreasing	24.0	276
3 (9-10 Dec)	0.0030 (11.3)	10	Little surface clogging	13.4, Decreasing	23.5	292
4 (10-11 Dec)	0.0040 (14.5)	8	Little surface clogging	14.2, Increasing	23.5	328
5 (11-12 Dec)	0.0040 (14.5)	10	Little surface clogging	14.4, Increasing	25.5	364
6 (12-16 Dec)	0.0060 (22.2)	9	No clogging	14.3, Increasing	71.5	988
7 (16 Dec)	0.0055 (19.5)	10	n/a	n/a	n/a	n/a

Generally, the hydraulic head profiles during drainage and backwash indicate that the flow in the sandbox occurs principally in the vertical axis above the half-conduit where the hydraulic gradient is highest. Also, it is here that surface clogging is initiated, to then progress laterally toward the left wall. Figure 3 shows some hydraulic head profiles during drainage sequence 3. In the vertical axis of the conduit, surface clogging is almost complete, but 1 m away there is much less clogging at the surface.

The results in Table 1 suggest that backwash operations with a flow rate less than 0.003 $m^3/s/m^2$ are not sufficient to declog the medium and recover the reference system capacity. Also, the hydraulic head profiles indicate that there is still clogging at the surface following backwash at these low rates. On the other hand, backwash operations with a flow rate greater than 0.004 $m^3/s/m^2$ allowed recovery to the reference system capacity during the subsequent drainage cycle, and indeed to slightly improve this capacity. The backwash operation with a flow rate of 0.006 $m^3/s/m^2$ resulted in an almost 2.5-fold increase in duration and volume drained during the subsequent drainage phase, before clogging occurred again.

Examination of the hydraulic head profiles during these tests shows that the backwash efficiency is higher in the vertical axis above of the half-conduit and decreases laterally. Figure 4 shows that the hydraulic head profiles are linear in the vertical axis of the conduit after a backwash operation. Also, during the surface scraping operations after backwashing, there are more fine particles and fine sands at the surface 1 m away from the half-conduit.

The breakthrough curves obtained during backwash phases show that the efficiency of this operation is optimal in the first 10 minutes (Figure 5).

3.3 Physical phenomena

During the drainage and backwash experiments various physical phenomena were observed from the Plexiglas window on the half-conduit side of the sandbox. These phenomena suggest both advantages and disadvantages in the operation of a horizontal riverbed filtration system.

3.3.1 Air exsolution

During drainage, when the surface of the porous medium becomes clogged, the medium below the clogged surface can go under tension. This buildup of negative pressure head causes air exsolution from the water, and the air phase that is thus created migrates upward toward the surface and accumulates just below the clogged zone. The presence of an air phase (unsaturated zone) causes a progressive reduction of the hydraulic conductivity of the porous medium.

When surface clogging induces a loss of capacity by more than the two-thirds threshold used in this study, the half-conduit is closed and backwashing is initiated. During the break in water flow between the end of drainage and the start of backwashing, the accumulated air phase migrates through the clogged surface and hydraulic heads attain hydrostatic equilibrium. This process causes a partial cleansing of the clogged surface. This implies that in an operational context, any break in operation can result in a partial cleansing of the clogged zone, thereby extending the efficiency of the filtration system. During the backwash operation, air phase migration continues and induces a surface shaking of particles that could be observed through the Plexiglas window.

This phenomenon presents a second advantage in the backwash operation. The air phase migration toward the porous medium surface creates preferential pathways where the velocity of water is higher than in the surrounding medium. This allows faster migration of the fine particles in the porous medium toward the surface, thereby again abetting cleansing and declogging of the filtration system.

3.3.2 *Quicksand conditions*

During the backwash operations, quicksand conditions were observed when backwash flow rates were 0.0055 and 0.006 $m^3/s/m^2$ (sequences 6 and 7 in Table 1). This occurred in the vertical axis of the half-conduit, in the first 50 cm below the surface composed principally of sand, and it induced an expansion of the porous medium by 2.5 cm (Figure 6).

In an operational context during backwash operations, it is possible that such an expansion allows a partial removal of the porous medium above the conduit. On the other hand, in the backwash tests where such quicksand conditions were observed, this expansion is possibly also linked to the enhanced performance (drainage duration and drained volume) in the subsequent drainage cycle (Table 1).

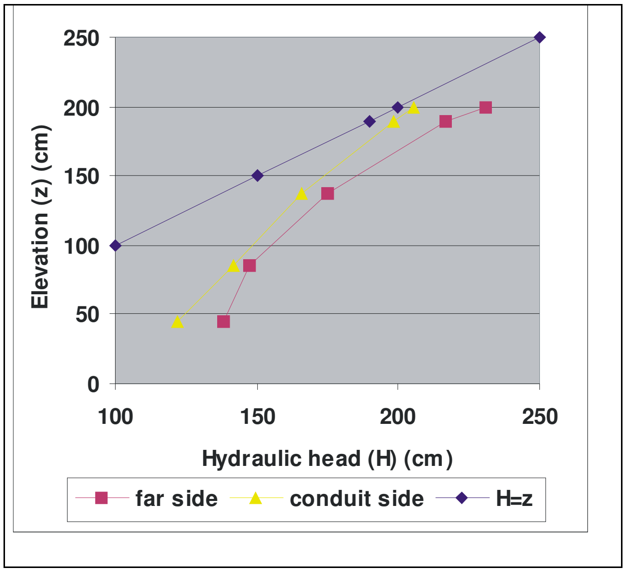

Figure 3: Hydraulic head profiles during the clogging phase in drainage sequence 3 (pressure gage readings).

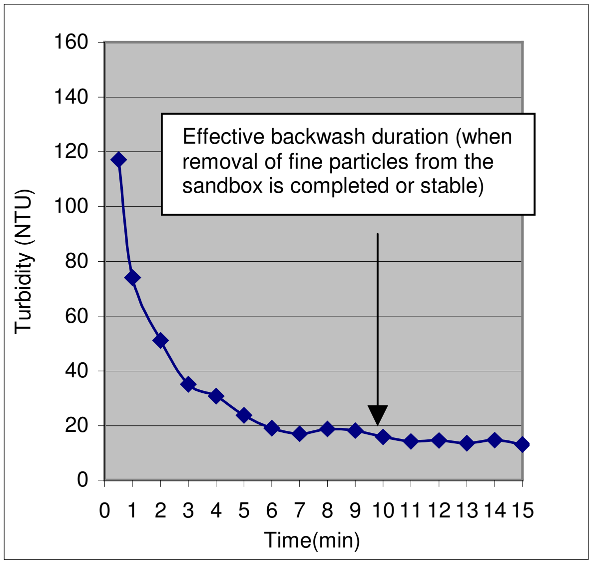

Figure 5: Backwash breakthrough curve for sequence 3.

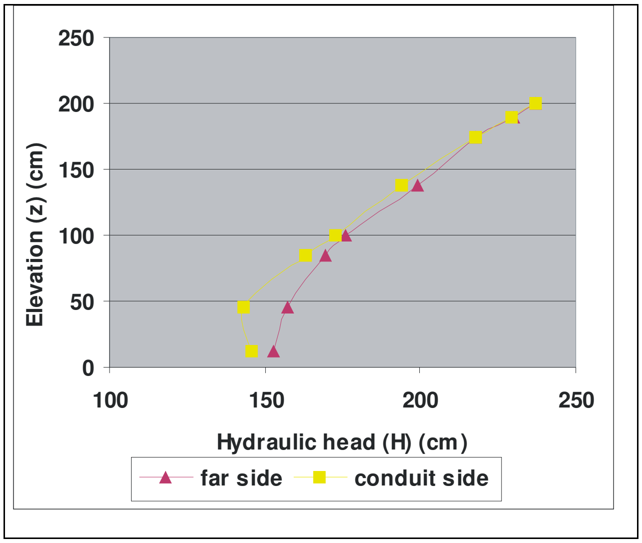

Figure 4: Hydraulic head profiles after a backwash operation (manual readings).

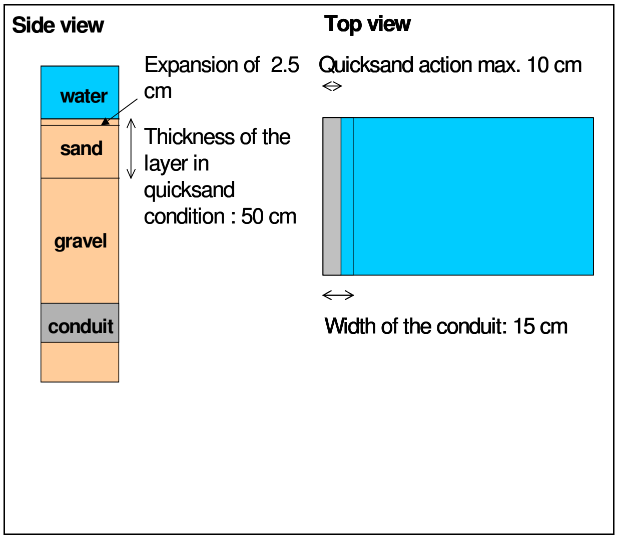

Figure 6: Quicksand conditions observed during backwash tests with flow rates of 0.0055 and 0.006 $m^3/s/m^2$.

3.3.3 *Fine sand migration during backwash operations*

During each backwash operation, there is migration of fine sand in the porous medium toward the surface. This phenomenon indicates that a grain size fraction of the medium is unstable during backwash. This migration occurs in part along the preferential pathways created by the air phase displacements described previously. Moreover, when there are quicksand conditions in the upper part of the medium, the particles get sorted with the fine fraction repositioned at the surface of the sandbox.

The presence of a uniform fine sand layer close to the surface of the horizontal riverbed filtration system can affect the drainage duration in an important way. This filter layer is prone to faster clogging. If these particles can be transported by the river current, the fine sand migration would be beneficial for the system capacity because it would allow cleansing under the surface. However over the long term, the sand loss during backwash operations will decrease the volume of the filtration medium. This loss may possibly be offset by deposition of new particles in the upstream river current, and if not, new material can be readily introduced during maintenance of the system.

4. CONCLUSIONS

The laboratory sandbox experiments described in this report suggest that the desired 70 000 m^3/d flow rate for a proposed horizontal riverbed filtration system in the Montmorency River near Quebec City can readily be met. After adequate development of the porous medium in the sandbox, upscaled drainage flow rates as high as 391 000 m^3/d were achieved.

Drainage sequences using turbidity levels at least twice as high as those found in the Montmorency River during winter were used to generate surface clogging. Water flow was found to be principally localized along the vertical axis of the half-conduit, where surface clogging is initiated during drainage. Surface clogging then progresses laterally until the surface sediments of the sandbox are completely clogged. This engenders an almost total loss of system capacity, normally after about 24 hours of drainage.

The backwash tests showed that a duration of 10 minutes and a flow rate higher than 0.004 m^3/ s/m^2, equivalent to 2177 m^3/h for one conduit, can be effective in dislodging the fine particles that cause surface clogging, and can allow the system to recover and even slightly improve its capacity. Backwashing is most effective in the vertical axis of the conduit. The backwash operation with a flow rate of 0.006 m^3/s/m^2 resulted in a 2.5-fold increase in drained water volume during the subsequent drainage cycle. However, this backwash test induced quicksand conditions in the vertical axis of the conduit and a 2.5 cm expansion of the medium. Other physical phenomena observed during the drainage and backwash experiments that can have positive or negative impacts on an operational riverbed filtration system include air bubbling and fine sand migration.

5. ACKNOWLEDGEMENTS

This study was made possible with funding from the municipality of Quebec City (Ville de Québec). The authors wish to thank Denis Pinard (Génio Experts-conseils inc., Beauport, Québec) and Michel Leclerc (INRS-ETE) for useful discussions and contributions to the project.

6. REFERENCES

Birch, S., R. Donahue, K. W. Biggar and D. C. Sego (2004). Prediction of flow rates for potable water supply from directionally drilled horizontal wells in river sediments. In: *57th Canadian Geotechnical Conference / 5th Joint CGS/IAH-CNC Conference*, CD-ROM, Canadian Geotechnical Society.

Kawecki, M. W. (2000). Transient flow to a horizontal water well. *Ground Water*, 38(6), 842-850.

Racine, C., C. Paniconi, R. Lefebvre, M. Leclerc and D. Pinard (2005). Analyse numérique d'un concept de prise d'eau sous-fluviale horizontale. In: *58th Canadian Geotechnical Conference / 6th Joint CGS/IAH-CNC Conference,* CD-ROM, Canadian Geotechnical Society.

Ray, C., T. Grischek, J. Schubert, J. Wang and T. Septh (2002). A perspective of riverbank filtration. *Journal of the American Water Works Association,* 94(4), 149-160.