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Assessing Alternative Media for Ballasted Flocculation

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Abstract

Most current commercial applications of ballasted flocculation use silica sand to increase floc size and density. Other ballast media with different specific gravity may offer advantages such as increased applicable superficial velocity or increased particulate matter removal. This study assessed the relative impact of five ballast media on ballasted flocculation/settling performance: anthracite, recycled crushed glass, conventional silica sand, garnet sand and magnetite sand, with a common d_{50} of 150 µm but variable specific densities of 1.45, 2.58, 2.62, 3.93 and 5.08, respectively. Based on microscopic observations and assuming discrete particle removal in an ideal settler, mean superficial media settling velocities were respectively calculated as 35, 73, 74, 122 and 137 m/h. These values do not account for the impact of lamella or other specific geometries of different patented clarifiers (*e.g.* CoMag®, Densadeg®, Sirofloc® and Actiflo®). Although the use of magnetite sand allows the total suspended solids load to increase by more than twofold compared to silica sand, the residual turbidity increased after settling as the mixing intensity needed to maintain denser media in suspension was augmented. Consequently, the lowest residual turbidity (0.78 NTU for surface water and 1.38 NTU for wastewater) was observed when anthracite was used as the ballast medium. The ballast media geometry did not significantly impact turbidity removal and settling velocity. Hence, recycled crushed glass was identified as a potential alternative to conventional silica sand despite its higher angularity.

Keywords: *ballast media, floc specific gravity, floc size, particles removal, critical settling velocity*

Introduction

Settling is one of the most common water treatment processes. Reducing particle loading before filtration or recovering suspended solids after an activated sludge treatment are common gravity separation applications. The pulp and paper and mining industries also use clarifiers to remove organics and/or particulate matters. One of the main drawbacks of conventional settling lies in its significant footprint. Increasing settling velocities by incorporating a ballast medium (BM) (typically sand) within flocs was proposed in the 1980s (Sibony, 1981) as an effective method for reducing the process footprint. For example, the Actiflo® process has been validated in Quebec (Canada) for settling rates up to 85 m/h for drinking water applications (MDDEP, 2009). Even under high superficial velocities, ballasted flocculation/settling may provide good removal of total suspended solids (TSS) and turbidity (>85 % and > 90 %, respectively, according to Plum et al. (1998)).

Compared with conventional flocculation systems, ballasted flocculation is operated under high mean velocity gradients (*G*) because a minimal mixing intensity must be induced in the water to maintain the BM in suspension (G=160-200 s^{-1}) (Desjardins et al., 1999). The minimal *G* value is controlled by the media specific gravity and size, *i.e.,* denser and larger BM require higher mixing. The specific gravity of ballasted flocs is mainly dependent on the specific gravity of the BM and its degree of incorporation into the floc structure (Lapointe & Barbeau, 2016b). Most ballasted flocculation studies have been conducted with silica sand (SS) (De Dianous & Dernaucourt, 1991; Desjardins et al., 2001; Lapointe & Barbeau, 2015; Young & Edwards, 2000). However, an alternative BM could have important advantages over SS in some applications: 1) a denser BM increases the specific gravity and settling velocity of flocs for high-rate clarification, 2) BM with sorbing-desorbing properties could simultaneously ballast flocs and adsorb contaminants; magnetite sand could possibly ballast flocs and remove arsenic, 3) other materials such as dolomite can be used to simultaneously increase alkalinity (Piirtola et al., 1999) and 4) a lighter BM could be used to reduce the mixing intensity, which limits the shear on sensitive floc structure. BM with higher densities than SS, such as magnetite and apatite (Piirtola et al., 1999), have been tested in the past, but no study has yet assessed the fundamental impacts of variable BM specific gravity on floc morphology (density, size and aspect ratio) and the resulting settling velocity distributions. Such information is critical for identifying the optimal settler design, *i.e.,* the settling velocity needed to remove all ballasted flocs.

This study presents a comprehensive evaluation of ballasted floc characteristics (settling velocity, specific gravity, size and shape) produced from five alternative media: anthracite (ANT), silica sand (SS), crushed glass (CG), garnet sand (GS) and magnetite sand (MS). The BM were tested both for drinking and municipal wastewater applications. We propose that an improved insight into ballasted floc characteristics will help in selection of the appropriate medium for a given settling application. Considering that many factors impact the ballast flocculation procedure, this study presents a method to assess objectively the particulate matter removal efficiency and the floc settling velocity distribution for various BM. More specifically, the objectives were to 1) evaluate optimal flocculation conditions for each BM (chemical dosages, BM concentration and mixing intensity), 2) assess the impact of the BM specific gravity on floc settling velocity distributions under optimal flocculation conditions (established in 1), 3) determine the role of BM shape on settling performance by comparing BM of variable angularity but identical density and size, and 4) identify the optimal BM for a given design criterion based either on a targeted turbidity removal or a designed superficial velocity.

Material and methods

Water characteristics

All experiments were conducted at laboratory scale using either 1) surface water (SW) from the Sainte-Rose drinking water treatment plant, which is fed by the Mille-Îles River (Quebec, Canada), or 2) municipal wastewater (WW) from the Repentigny (Quebec, Canada) water resource recovery facility (collected after the 6 mm influent bar screens). The water characteristics assessed before coagulation and after flocculation and settling (and the associated analytical methods) are presented in Tables 1 and 2.

Ballast media characteristics

To avoid the potential confounding effect of ballast media size distribution on performance (Lapointe & Barbeau, 2015), an identical media size distribution was generated for all BM by sieving. The d_{10}, d_{50}, d_{60} and the uniformity coefficient were 98 μm, 150 μm, 162 μm and 1.65, respectively. The main BM physical properties anticipated to have an impact on settling velocity once integrated into a floc structure are listed in Table 3. The *G* numbers correspond to the minimum values needed to maintain the grains in suspension during a jar test, hence allowing each grain to potentially contribute to the ballasted flocculation.

Identification of optimal coagulation conditions

Bench-scale test experiments were conducted in 2-L square B-KER[2] jars (Phipps & Bird). The water was first coagulated by flash-mixing for 2 minutes with alum ($G=300\ s^{-1}$). The coagulation mechanisms expected for both waters tested were charge neutralization and sweep coagulation (mostly sweep coagulation in the case of the wastewater tested). Flocculation was then initiated by the simultaneous injection of a BM and polymer. Optimal alum dosages for both water types (0.40 mEq/L for SW and 1.41 mEq/L for WW) were determined based on turbidity removal (*i.e.,* when an asymptote was observed on the turbidity versus coagulant curve). For the SW, the optimal coagulation dosage was also established based on UVA_{254} (80 % removal), dissolved organic carbon (DOC; 55% removal), pH of coagulated water (6.4), residual alkalinity after coagulation (15 mg $CaCO_3$/L) and the streaming current value (SCV) as an indicator of particle residual charge (SCV = 0 for a coagulant dosage of 0.38 mEq./L). The SCV was not a good indicator for the WW tested because it overestimated the coagulant dosage needed (SCV=0 at 4.65 mEq/L, which was 3.3 times the dose required to obtain the minimal turbidity). This overestimation can be explained by the high concentration of particles, which led to important sweep coagulation, interception and enmeshment mechanisms. Therefore, the optimal alum dosage that was needed to coagulate the wastewater was determined by relying on the removal efficiency of TSS, turbidity, total phosphorus and soluble phosphate.

Laboratory scale ballasted flocculation

Different *G* values (from 100 to 300 s^{-1}) were tested during flocculation to account for the differing BM densities. The Superfloc® A-100 polymer, an anionic high molecular weight polyacrylamide (PAM) from Kemira, was used to bridge BM with the microflocs. After floc maturation (1 min was sufficient to complete floc formation for all media) and settling (3 min), the settled waters were characterized by particle count, residual TSS and turbidity measurements. Settling times longer than 3 min did not provide significant improvements in settling performance. Optimal *G* values were established from turbidity measurements in settled waters.

Ballasted flocculation performance

Ballasted flocculation performance was assessed in terms of 1) turbidity removal after settling and 2) calculation of theoretical floc settling velocity distributions based on floc characteristics derived from microscopy analysis. This twofold approach offers the ability to distinguish between the performance of flocculation (*i.e.,* quality of flocs formed leading to high settling velocity) versus the performance of settling (*i.e.,* particle removal for a specific settling time or simulated settler superficial velocity). Turbidity was the preferred option for estimating particle removal due to its simplicity and the high correlation observed between turbidity and TSS removal during preliminary assays. Theoretical floc settling velocity distributions were calculated according to the method described in Lapointe and Barbeau (2016b). In this procedure, forty individual ballasted flocs are characterized for their shape, diameter and density using microscopic analysis. The Stokes' equation (for $Re < 1$) and Newton's equations (for $1 < Re < 1000$), as proposed by Johnson, Li, and Logan (1996), are then used to predict floc settling velocity distributions (assuming discrete settling).

Results

Impact of PAM dosage and BM concentration on settling performances

Dosages of 0.375 mg PAM/L for SW and 0.5 mg PAM/L for WW were selected as sufficient to provide an acceptably low settled water turbidity (Figures 1A, B and F). ANT, SS and CG had similar requirements for PAM dosage, while GS and MS needed more PAM to achieve the minimum settled turbidity. BM concentrations of 2 and 3 g/L were defined as appropriate for SW and WW, respectively (Figures 1C and D). Conclusions were identical whether particle counts or turbidity was used to evaluate performance (data not shown). For full-scale ballasted flocculation processes, BM concentrations in the range of 3 to 5 g/L for SW and 4-6 g/L for WW are commonly used. For a full-scale application, the BM concentration is generally above the optimal concentration as raw water turbidity fluctuations and BM export in settled water have to be considered in the design.

Particulate matter removal under optimal conditions

Figure 2 presents the settled water turbidities achieved under optimal coagulation/flocculation conditions. Good turbidity removals of 80-90 % and 97-99 %, depending on the BM, were achieved in SW and WW, respectively. Residual turbidity after settling increased as the mixing intensity needed to maintain denser BM in suspension was augmented. Consequently, the lowest residual turbidity was observed when ANT was used as the BM, even though it was the lightest medium tested. For both water sources, ANT produced the lowest residual particle concentration (0.78 nephelometric turbidity unit (NTU) in SW and 1.38 NTU for WW). The better performance of ANT is explained by the lower shear required in the tank (G = 100 s^{-1}) to maintain the medium in suspension. Nevertheless, for all BM and water types, a turbidity removal higher than 80% was always attained.

The impact of BM angularity can be assessed by comparing the performances of silica sand and crushed glass (Figure 2). Both media have similar specific gravity but considerably different geometry (L/l ratios of 1.44 and 2.05, respectively; Table 3). Both media produced equivalent settled water turbidity, which suggests a negligible impact of the BM aspect ratio on process performance.

Impact of mixing intensity on particle removal and energy consumption

For each BM investigated, optimal G values were identified to minimize settled water turbidity. The optimal G was always the minimum value needed to maintain the BM in suspension (data not shown). Too low of a G value reduces the concentration of BM available for ballasting. A higher G value increases floc breakage. For both source water types, Figure 3 indicates that the residual turbidity after settling (3 min) was inversely correlated to the G value employed during flocculation. The residual turbidity was confirmed microscopically to be caused by un-ballasted microflocs. The energy consumption for each BM was calculated using the optimal G value. Considering that all of the BM had identical grain size distributions, MS and GS consumed 2.4 and 1.7 times more energy, respectively, compared to SS. The required energy for ANT corresponded to only 37% of the energy needed for SS. A similar energy consumption was estimated for SS and CG, as comparable optimal *G* values had been identified for both media.

Predicted floc settling velocity based on microscopic observation

Floc size and specific gravity

Floc size and specific gravity characterization through microscopic observation permitted calculation of floc settling velocity distributions. The mean floc diameter, BM incorporation (i.e., the percentage of the volume of the floc made up of BM), the aspect ratio and the specific gravity for each tested medium are listed in Table 4. Under optimal mixing conditions, ANT produced the largest ballasted flocs (553 μm, 22 % larger than by conventional SS, *t*-test, $p < 0.05$), but the lowest BM incorporation ($p < 0.05$) and hence, the lowest floc specific gravity (1.09, 16 % lower than SS, $p < 0.05$). In contrast, MS produced the smallest flocs (390 μm, 14 % smaller than by SS, $p < 0.05$). However, a relatively high BM incorporation (20.1%, a proportion 22 % higher than SS) and specific gravity (1.84, 43 % denser than SS, $p = 0.07$) were achieved when MS was employed as the BM. Similar floc characteristics were observed between GS and SS. BM incorporation and floc size were proportional and inversely proportional, respectively, to the mixing intensity (expressed in terms of *G*).

Predicted settling velocities

Settling velocity is controlled by ballasted floc density, size and, to a lesser extent, shape. Settling velocity distributions were predicted based on the individual assessment of 40 flocs produced in SW with various BM (Figure 4). Mean settling velocities varied from 35 m/h (ANT) to 137 m/h (MS). GS and MS exhibited similar settling velocity distribution profiles, even though their specific gravities were considerably different (3.93 for GS vs. 5.08 for MS). The lower density of the flocs ballasted with GS was partially compensated by the formation of larger aggregates compared to those formed with MS. CG and SS produced nearly identical settling velocity distributions despite their different geometries.

Critical superficial velocity for TSS removal

For some applications, the criterion of settling performance is TSS removal (expressed in flux of solids removed, kg of TSS removed h^{-1} m^{-2}) rather than residual turbidity in the settled water. For SW prior to settling, the TSS in the jar test was estimated at 2,040 mg/L, which was calculated by the sum of the BM concentration (2,000 mg/L), the alum precipitate (10.5 mg/L of precipitate), the PAM added (0.3 mg/L), the DOC removed (3.8 mg C/L) and the initial TSS (24 mg/L). The TSS are mostly composed of BM (98.1% in this example). With the use of the floc characteristics (size, density shape and settling velocity) obtained by microscopy, TSS removal can be predicted for various superficial velocities. For this calculation, it was assumed that flocs having a settling velocity higher than the settler velocity were entirely removed, whereas flocs with a lower settling velocity remained in the supernatant. Figure 5 presents the predicted residual TSS in settled waters for increased settling velocities and variable BM. A critical superficial velocity, *i.e.,* the maximal velocity not to be exceeded to remove all ballasted flocs, can be identified for each BM. For superficial velocities under the critical velocity, only un-ballasted flocs will be found in settled waters. Critical velocities at 22°C (identified as empty squares on the inset of Figure 5) varied between 10 m/h for ANT to 40 m/h for MS. It is important to point out that the procedure does not precisely predict the full-scale performance of ballasted technologies (e.g. CoMag® and Sirofloc® with magnetite or Actiflo® with silica sand). Full-scale clarifiers performance also depends on the hydrodynamic and other phenomena such as flocs aggregation into the lamella and energy gradient distribution inside the process. For example, full-scale Actiflo® settlers with silica sand are commonly designed at velocities of 60 m/h, which is a value higher the critical value of 17.5 m/h calculated for SS in this study.

The plateaus of TSS observed below critical velocities are explained by un-ballasted flocs, which are not removed if the superficial velocity is above 1 m/h. Using these critical velocities, TSS loadings (excluding the BM) were calculated at 22°C and expressed as kg of TSS removed h^{-1} m^{-2}. These values were 0.37, 0.54, 0.64, 1.23 and 1.38 kg of TSS h^{-1} m^{-2} for ANT, CG, SS, GS and MS, respectively. Consequently, the use of MS increases the TSS load by almost fourfold compared to ANT. The costs for this improved settling are: (i) higher mixing energy and (ii) higher final TSS concentration due to floc breakage.

Figure 6A presents the raw water TSS removals for the five tested BM and identifies the maximal applicable superficial velocity for 100% removal of ballasted flocs (i.e., only un-ballasted flocs remain). This figure enables prediction of intermediate TSS removal performance (between 60% and the maximal value observed for each BM). The overall performance of the process results from two distinct mechanisms: the removal of ballasted and un-ballasted flocs. The data obtained in Figure 6B were compared with values collected from the scientific literature for laboratory scale jar tests using SS as the BM. The variability in these data is explained by the fact that the studies were conducted with different coagulant-polymer dosages, BM concentrations and size, water temperature and types.

Discussion

Effect of PAM dosage and BM concentration

In this study, identical BM concentrations (in terms of w/v) were used. However, because the five tested BM had different specific gravities, variable amounts of BM grains were injected and the numbers were inversely proportional to the BM specific gravity. Thus, ANT offered more than 12 times the surface area than did MS. Consequently, it was observed that a higher concentration of MS (on a w/v basis) was needed compared to SS (15 g MS/L vs. 5-8 g SS/L) to achieve a turbidity removal above 85% (Imasuen et al., 2004). During this study, we identified an optimal concentration of approximately 1-2 g SS/L for a SW application. This range corresponds closely to those observed by Sibony (1981) (0.8-1.8 g/L), Young and Edwards (2003) (1.25 g SS/L) and Desjardins et al. (2001) (1-2 g SS/L, turbidity < 0.25 NTU). However, Ghanem et al. (2007) observed an optimal density for ballasted flocs when higher SS concentrations were used (5-7 g SS/L).

The polymer molecular weight, which is more than several millions daltons in the case of PAM (Gaid & Sauvignet, 2011), largely influences the bridging mechanism during flocculation (Caskey & Primus, 1986). In theory, the PAM dosage needed to form proper aggregates (see Figures 1E and 1F) is proportional to the cumulative surface of all coagulated particles (Gregory & Barany, 2011). MS should have required the smallest PAM dosages because it offered the smallest total surface available for polymer chain adsorption. However, higher PAM dosages were required for optimal TSS removal by GS and MS. These increased flocculant demands are most likely explained by the higher shear forces on the floc structure (G value of 255 s^{-1} for MS) which were applied to maintain the BM in suspension. In this case, an increased PAM dosage could have compensated the negative impact of shear on floc size and BM incorporation into the floc. Additional visual information of the impact of mixing conditions on floc morphology can be found in Lapointe and Barbeau (2015b, 2016a, 2016b).

Floc characteristics and particles refractory to settling

This study focused on the characteristics that flocs must have to be properly removed during settling. Floc size, density and shape mainly control the settling rate (Johnson et al., 1996; Tambo & Watanabe, 1979). The floc shape was shown to be a minor parameter by Lapointe and Barbeau (2016b). The comparison between SS and CG confirmed the negligible impact of the BM shape. Hence, the main objective of ballasted flocculation is to produce the largest and densest flocs. Ballasted flocs have considerably higher specific gravity (1.1-2.0, depending on the BM used in this study and 1.2-2.0 in Young and Edwards (2000)) compared to conventional flocs (1.03-1.05, Larue and Vorobiev (2003)). However, this study revealed an inverse relation between the floc size and the BM specific gravity. Moreover, a direct relation was observed between the BM specific gravity and the non-settleable particle concentration. The increased *G* value, required to maintain a denser BM in suspension, augments the disaggregation of microflocs from the main floc structure. For each tested BM, two distinct floc size distributions were observed: ballasted flocs and un-ballasted flocs (Lapointe & Barbeau, 2016a). The concentration of small un-ballasted aggregates (with settling velocity < 1 m/h) dictated the final settled water turbidity. Thus this study highlights the importance of limiting the mixing intensity during ballasted flocculation to reduce the concentration of non-settleable particles. For WW, higher settling turbidity was observed compared to SW applications. The higher turbidity that is produced in settled WW is likely attributable to a less compact floc structure associated with a higher drag coefficient. For porous aggregates, shear forces are heterogeneously distributed into the structure (i.e., shearing planes are obtained when flocs have an expanded structure).

Floc size is related to numerous factors, including water type, coagulant/flocculant dosage, polymer type, size and density of BM used, and mixing intensity. For this reason, comparisons with other studies are difficult. As an example, while we measured ballasted floc sizes of 300-800 µm (polymer dosage: 0.375 mg/L, SS concentration: 2 g/L), Young and Edwards (2003) observed SS ballasted flocs having diameters ranging from 500 to 7,000 µm (polymer dosage: up to 10 mg/L and SS concentration: up to 10 g/L).

Ballast medium selection

The critical superficial velocity to remove 100% of ballasted flocs is an important reference, as with higher superficial velocities TSS removal decreases rapidly (11% removal decrease for each additional m/h in the case of ANT). This sharp increase of TSS concentration in settled water is attributable to exportable BM in settled waters (either incorporated or not into the floc). Denser BM, such as MS and GS, exhibit higher critical velocities. Using denser BM offers the ability to operate at higher velocities (and reduce footprint) as long as the residual turbidity in settled waters is acceptable. During this study, the turbidity of 1.7-2.0 NTU achieved with GS and MS in surface waters is relatively high and would therefore not be considered optimal for a drinking water application. On the other hand, for some other industrial applications in which higher settled water turbidity is acceptable and a small footprint is desirable (e.g., settling of combined sewer overflows), using a denser BM such as MS may prove a useful alternative to SS.

Independent of the BM used, a significant increase of the solid flux removal (kg of TSS m^{-2} h^{-1}) was observed compared to conventional flocculation (10-24 times when SS was used as BM and considering a superficial velocity between 0.71 – 3.3 m/h for conventional flocculation (Kawamura, 2000). Other parameters must be considered for the final comparison of all existing BM: costs material, geographic availability, stability, hydrocyclone separation effectiveness (directly proportional to BM specific gravity), energy costs to maintain particles in suspension and the impact of BM angularity on abrasion of the recirculation piping.

Conclusion

This study reports tests conducted with ballasted flocculation media as alternatives to SS. The final BM selection is a compromise between settled water quality and the highest applicable superficial velocity, the latter having a direct impact on capital and operational expenditures. This study revealed the advantages of operating ballasted flocculation with a BM having a relatively low specific gravity: lower *G* led to a reduction in energy consumption, lower shearing induced on floc structure and improved turbidity removal. However, certain industrial applications could benefit from the higher solids flux removal offered by denser BM. More specifically, this study concluded that:

- The critical theoretical superficial velocity can be calculated based on microscopic observations of ballasted flocs.
- ANT produced the best settled water quality while MS ballasted flocs had the highest mean superficial velocity.
- The BM angularity did not significantly impact turbidity removal. Hence, CG was established as a potential alternative to the conventionally used SS, especially for wastewater applications where the contamination of the BM is not an issue.
- SS is a good compromise for providing simultaneously low settled water turbidity and high solids flux removal.

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Table 1: Monitored parameters and associated analytical methods.

Parameters	***Units***	***Methods***
Total COD[1]	mg/L	Dichromate Reactor Digestion Method, Hach® Method 8000 High-range 20-1500 mg COD/L (Hach Company, 2014, Method 8000 DOC316.53.01099.) Potassium hydrogen phtalate standard solution, SM 5220 B. APHA et al., 2012)
BOD[2]	mg/L	SM 5210 B. (APHA et al., 2012)
TSS[3]	mg/L	SM 2540 D. (APHA et al., 2012)
VSS[4]	mg/L	SM 2540 E. (APHA et al., 2012)
Alkalinity	mg $CaCO_3$/L	SM 2320 B. (APHA et al., 2012), Mettler Toledo DL28 Electrometric Titrator
Total Phosphorus	mg P/L	In-line UV/Persulfate Digestion Method and Flow Injection Analysis, Lachat QuikChem® Method 10-115-01-3-A Range 0.10 to 10.0 mg P/L (Lachat-Instruments, 2001) SM 4500-P I. (APHA et al., 2012)
Soluble Phosphorus (S_{PO4})	mg P/L	Flow Injection Analysis, Lachat QuikChem® Method 10-115-01-1-A Range 0.01 to 2.00 mg P/L (Lachat-Instruments, 2001) SM 4500-P G.; (APHA et al., 2012) S_{PO4} was determined on the filtrate of 1.2 µm glass microfiber Grade 934-AH™ filter (Whatman™) and 0.45 µm cellulose membrane filter (EMD Millipore) superimposed
Turbidity	NTU	Turbidimeter, Hach 2100N, SM 2130 B. (APHA et al., 2012)
SCV[5]	-	Chemtrac® Systems, Inc. (ECA-2100 charge analyzer)
UVA_{254}	cm^{-1}	Settled waters filtered on a pre-washed 0.45 µm PES Supor®-450 membrane (Pall), (APHA et al., 2012)
Particle counts	# part./ml	Particles analyzer, Brightwell Technologies, DPA-4100
DOC	mg C/L	Sievers 5310c total organic carbon analyzer, GE Water, SM 5310 C. (APHA et al., 2012)
Floc size	µm	Counting cell (2 mm depth, Model # 1801-G20) Camera (Olympus DP70) Optical microscope (Olympus BX51) Equivalent diameter method (Lapointe & Barbeau, 2016b)
Floc specific gravity	-	Counting cell (2 mm depth, Model # 1801-G20) Camera (Olympus DP70) Optical microscope (Olympus BX51) Ballast media incorporation method (Lapointe & Barbeau, 2016b)

1: total chemical oxygen demand, 2: 5-day carbonaceous biochemical oxygen demand, 3: total suspended solids, 4: volatile suspended solids, 5: streaming current value

Table 2: Water characteristics and chemical dosages used during jar tests.

Parameters	***Units***	***Surface water (SW)***	***Wastewater (WW)***
Coagulation-flocculation conditions			
Alum dosage	mEq/L	0.40 (3.64 mg Al/L) [3]	1.41 (12.73 mg Al/L) [3]
PAM dosage	mg/L	0.375 [1]	0.5 [1]
BM concentration	g/L	2.0[1]	3.0 [1]
Raw water characteristics (unless specified otherwise)			
Turbidity	NTU	12.0 after settling: < 2.0 [4] (> 83% removal)	130 after settling: < 4 [4] (> 97% removal)
Particles concentration	#/mL	250 000 after settling: < 10 000 [4] (> 96% removal)	-
COD	mg/L	-	613 (> 60% removal)
BOD	mg/L	-	215 (> 55% removal)
DOC	mg C/L	raw: 6.9 after settling: 3.1 [2] (55% removal)	-
TSS	mg/L	24 after settling: < 5 [4] (> 80% removal)	266 after settling: < 8 [4] (> 97% removal)
VSS	mg/L	-	229
pH	-	raw: 7.5 after settling 6.4 [2]	raw: 7.8 after settling: 7.4 [2]
Alkalinity	mg $CaCO_3$/L	raw: 35 (consumed: 57%) after settling: 15 [2]	raw: 305 (consumed: 23%) after settling: 235 [2]
UVA_{254}	cm^{-1}	raw: 0.244 after settling:0.049 [2] (80 % removal)	-
Total Phosphorus	mg P/L	-	raw: 7.70 after settling: < 0.17 [2] (98% removal)
Soluble Phosphorus (S_{PO4})	mg P/L	-	raw: 4.60 after settling: < 0.06 [2] (99% removal)

[1] Optimal dosage retained for comparison (cf. PAM = Polyacrylamide
[2] Similar observations for all BM and independent of PAM dosage
[3] See section *Identification of optimal coagulation conditions*
[4] Removals obtained with optimal PAM dosage and BM concentration

Table 3: Ballast media physical properties and minimum mean velocity gradient needed to maintain the media in suspension during flocculation.

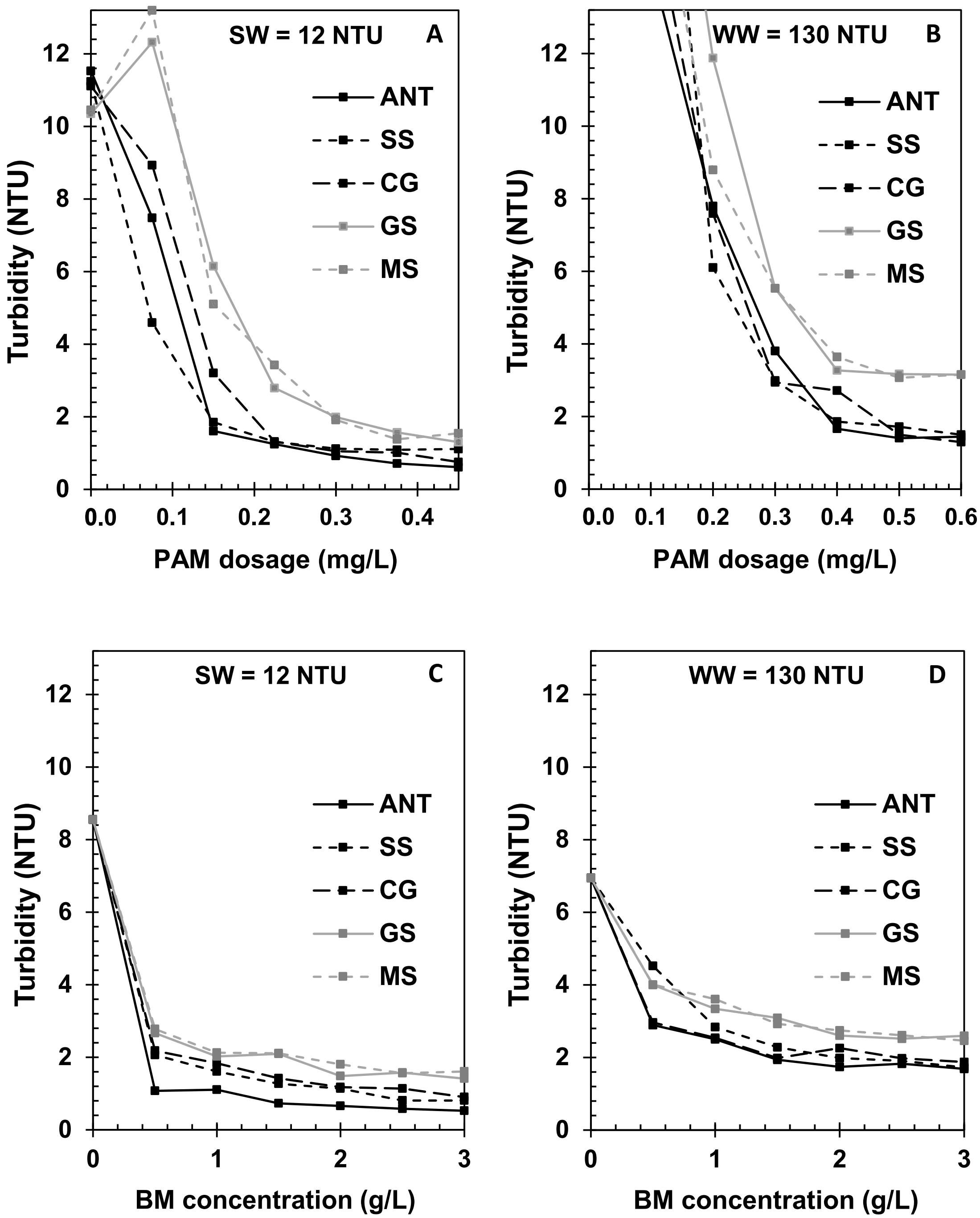
Ballast media	***Specific gravity***	***Mean ratio L/l*** [1]	***Hardness***	***Minimum G (s^{-1})***	***Point of zero charge (PZC)*** [2]
Anthracite (ANT)	1.45	1.61	2.2 - 3.0	100	7
Silica sand (SS)	2.62	1.44	6.0 - 7.0	165	< 3 (Kim & Lawler, 2005; Kosmulski, 2011)
Crushed glass (CG)	2.58	2.05	5.5 - 7.0	165	< 3 (Kosmulski, 2011)
Garnet sand (GS)	3.93	1.93	7.5 - 8.0	215	3.5 – 4 (Kosmulski, 2009)
Magnetite sand (MS)	5.08	1.36	5.5 - 6.5	255	6.5-6.7 (Kosmulski, 2011)

[1] Floc and BM shapes are characterized as an ellipse (*L* and *l* represent the longest and the shortest ellipse dimensions, respectively)
[2] Between 20-25 °C

Table 4: Floc diameter, BM incorporation and specific gravity obtained under optimal conditions.

BM	Floc mean diameter (µm)	Mean BM incorporation (%)	Floc mean specific gravity	Floc mean aspect ratio (L/l)
ANT	553 ± 16	13.2 ± 0.3	1.09 ± 0.03	1.80 ± 0.06
SS	454 ± 18	16.5 ± 1.6	1.29 ± 0.06	1.74 ± 0.11
CG	465 ± 17	16.6 ± 0.8	1.29 ± 0.05	1.88 ± 0.23
GS	403 ± 13	22.7 ± 0.4	1.69 ± 0.04	1.80 ± 0.09
MS	390 ± 10	20.1 ± 0.1	1.84 ± 0.02	1.74 ± 0.09

Errors correspond to standard deviations
Mean BM incorporation: volume fraction of the floc composed of BM


SW = 12 NTU
A
WW = 130 NTU
B
SW = 12 NTU
C
WW = 130 NTU
D
ANT
SS
CG
GS
MS
Turbidity (NTU)
PAM dosage (mg/L)
BM concentration (g/L)

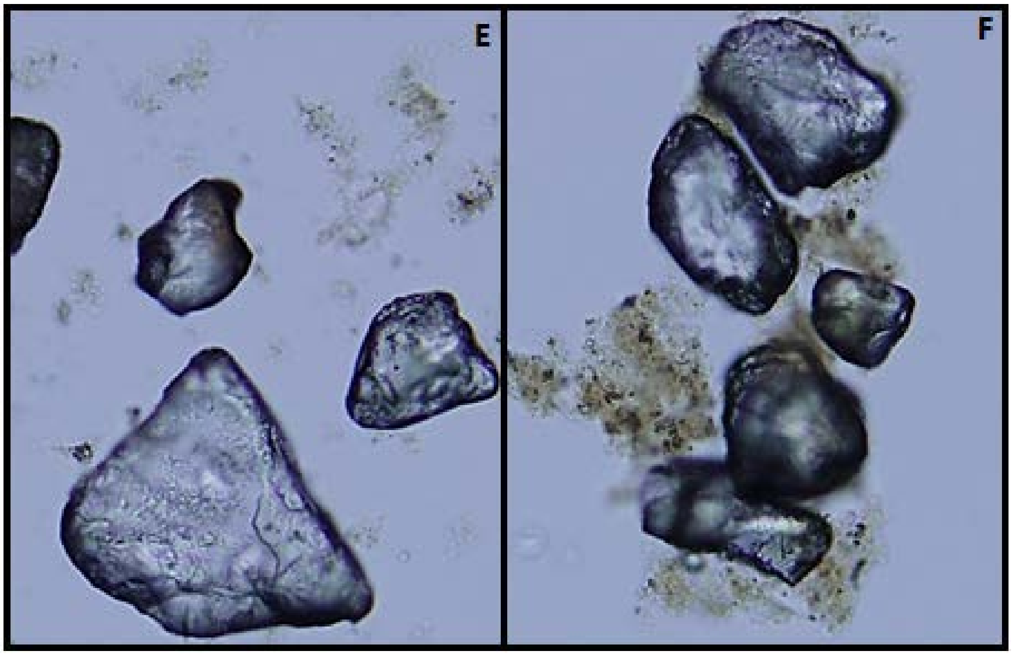


Figure 1: Settled water turbidity for variable PAM dosages for A) SW and B) WW (Conditions: BM = 4 g/L, flocculation time = 1 min at optimal *G*, settling time = 3 min) or variable BM dosages for C) SW and D) WW (Conditions: PAM = 0.375 mg/L (SW) and 0.5 mg/L (WW), flocculation = 1 min at optimal G, settling time = 3 min). Images in E) and F) illustrate the impact of low (0.10 mg/L) and optimal (0.375 mg/L) polyacrylamide dosage on silica sand aggregation (surface water), respectively. Maximal standard deviation: 0.31 NTU (for polyacrylamide dosages higher than 0.15 mg/L). Temperature: 21°C.

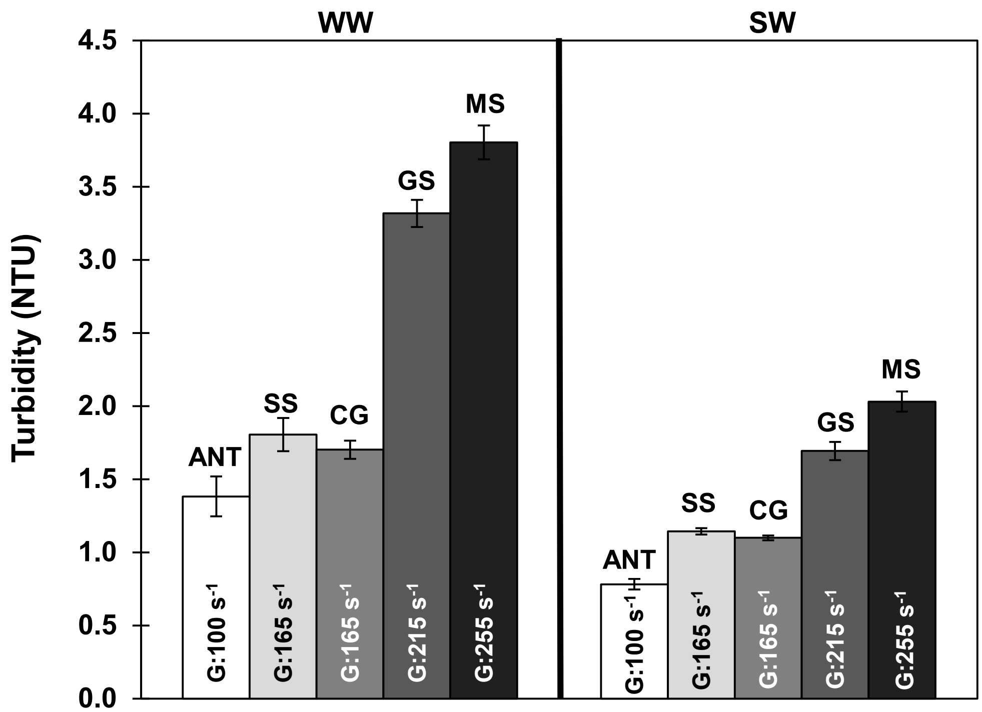


Figure 2: Settled water turbidity achieved under optimal coagulation/flocculation conditions. Conditions: PAM = 0.375 mg/L (SW) and 0.5 mg/L (WW), BM dosage: 2 g/L (SW) and 3 g/L (WW), flocculation time = 1 min, settling time = 3 min. Error bars correspond to the standard deviation. Temperature: 21°C.

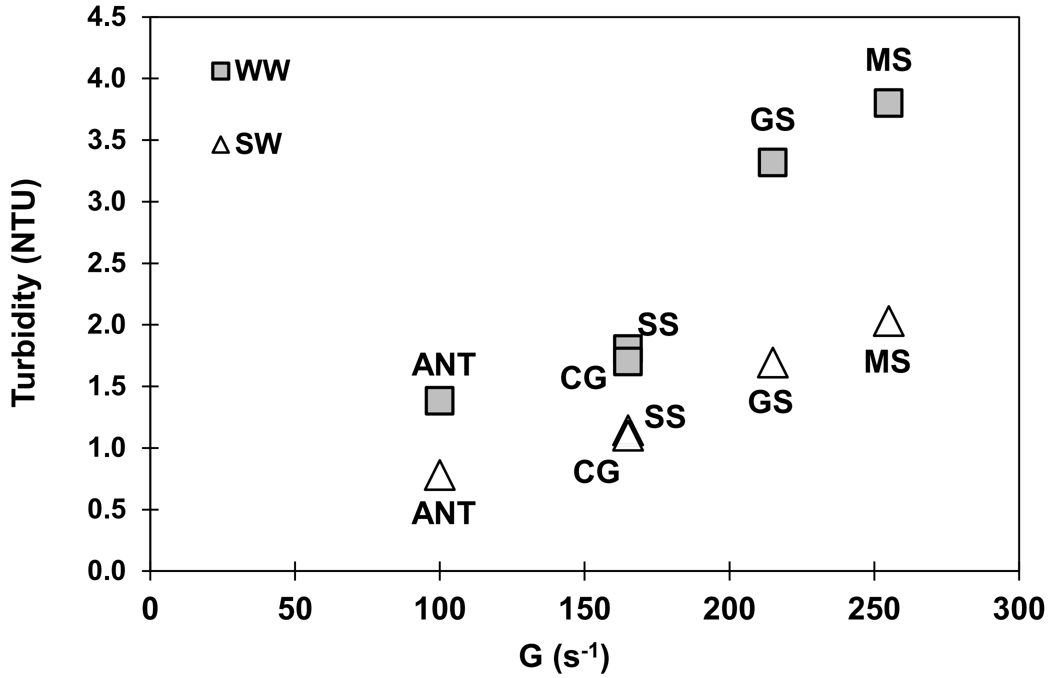


Figure 3: Settled water turbidities achieved under optimal *G* for each ballasting medium. Conditions: PAM = 0.375 mg/L (SW) and 0.5 mg/L (WW), BM: 2 g/L (SW) and 3 g/L (WW), flocculation time = 1 min, settling time = 3 min. Maximal standard deviation observed = 0.14 NTU. Maximal standard deviation for any media: 0.14 NTU. .. mperature: 21°C

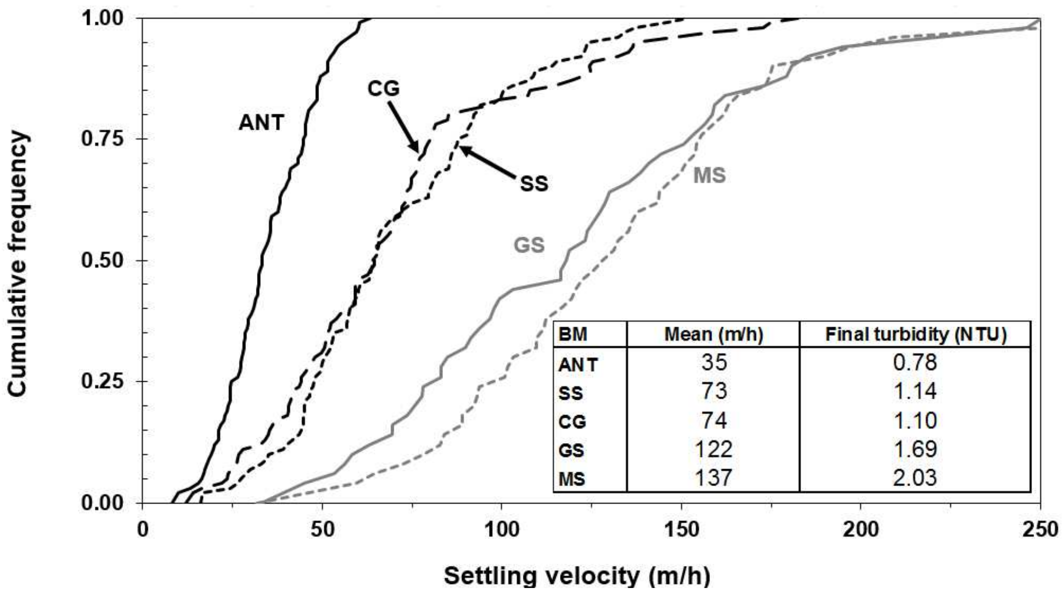


Figure 4: Cumulative frequency distributions of predicted floc settling velocity for 5 BM tested in surface waters. Conditions: PAM = 0.375 mg/L, BM: 2 g/L, flocculation time = 1 min, settling time = 3 min. Temperature: 21°C.

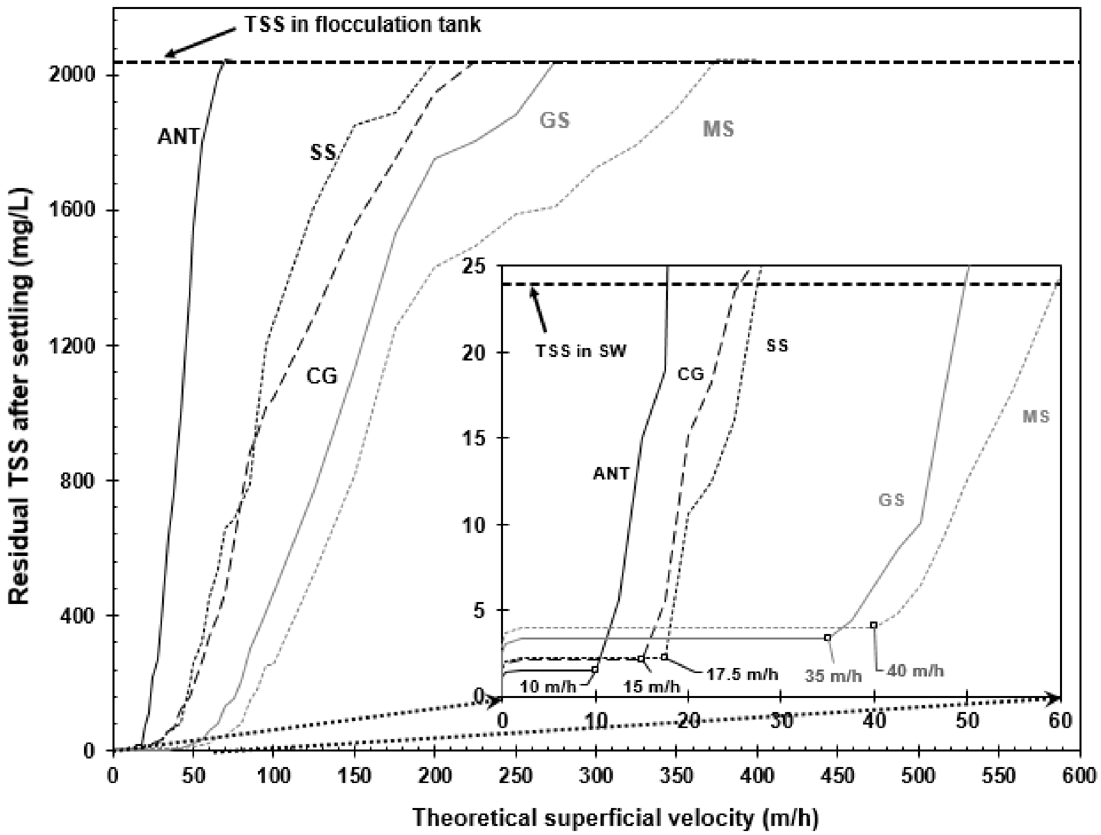


Figure 5: Predicted residual TSS in settled water for increasing superficial velocities at 21°C. Inset: Empty squares = Maximal superficial velocities needed to remove all ballasted flocs i.e., to obtain the ultimate residual TSS. Conditions: PAM = 0.375 mg/L, BM: 2 g/L, flocculation time = 1 min, settling time = 3 min.

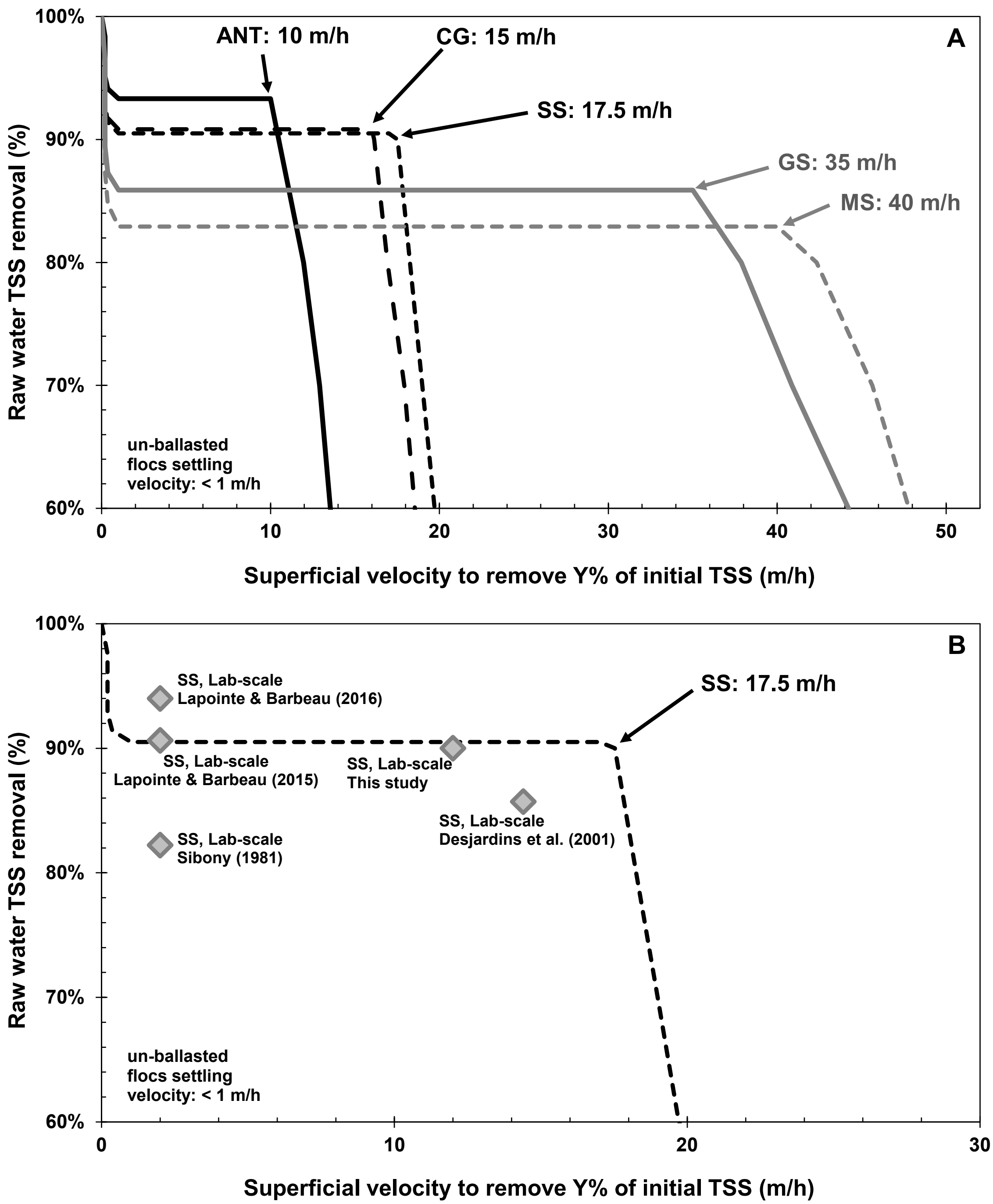


Figure 6: A) Relation between the raw water TSS removal and superficial velocity. B) TSS removals compared with values from the scientific literature (lab-scale). Conditions for this study: PAM = 0.375 mg/L, BM: 2 g/L, flocculation time = 1 min, settling time = 3 min. Temperature: 20-23°C.