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# OPTIMIZATION OF BALLASTED SAND FLOCCULATION PROCESS FOR URBAN RUNOFF TREATMENT

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## ABSTRACT

*Urban runoff contains suspended sediments, organics and nutrients which are detrimental to the health of receiving water bodies, especially lakes in the hilly areas. Jar tests based on ballasted sand flocculation (BSF) process were conducted to evaluate the treatment strategy for 1 MLD pilot plant installed in hilly catchment (Nainital) for urban runoff treatment. The BSF is a new physico-chemical treatment process which requires less land footprint in comparison to conventional coagulation-flocculation processes. For the envisaged objectives, water samples were collected in the monsoon seasons of year 2016 and 2017 from a major stormwater drain (Naina Devi drain) of the Nainital Lake catchment area. The micro-sand ballasted jar tests were conducted thrice for optimizing chemicals dosage and twice for comparing the jar test results with the treatment efficiency of a full scale pilot plant application. Alum and cationic polyelectrolyte were used as a coagulant and coagulant aid, respectively. The optimized alum dosage of 20-80 mg/l and polyelectrolyte dosage of 0.5-1.2 mg/l was found to be most effective for suspended solids removal along with other pollutants. Commercially available silica sand of size 130 µm and dosage of 10 gm/l was used for the experiment. The micro-sand ballasted jar tests results indicated that the removal of total suspended solids, total phosphorous, COD, BOD, Zn, Cu and Pb up to 99%, 94%, 82%, 78%, 66%, 66% and 78% respectively was achievable. The characteristics of the effluent/settled water from pilot plant (field-scale) and the jar test (lab-scale) were compared and minimal variation in the treated water was observed.*

***Key Words**: Jar test, ballast, coagulant, runoff, Nainital*

## INTRODUCTION

Most cities and towns in India are now undergoing rapid population growth, urbanization and industrialization. These developments have resulted in increasing water pollution problems and are deteriorating the water quality of the surface water bodies. Due to exponential rise of impervious land in urban areas, stormwater runoff is generated with higher peak (Zhao et al., 2007) and pollutants accumulated on surface are carried away into receiving water bodies (Brezonik and Stadelmann, 2002). Number of studies reported that urban non-point source pollution is an important contributor to water quality degradation (Davis and Birch, 2010; Palla et al., 2009). Surface water bodies such as lake face the problem of siltation and eutrophication due to catchment's stormwater runoff (Landon et al. 2006). Nainital Lake (India), a lake of national importance is one such water body which faces the water quality problem because of human intervention in the catchment of the lake (NIH 2000; Dash et al. 2008; Singh et al. 2016). Nainital Lake is the main source of water supply for Nainital city and also attracts thousands of tourists every year due to its scenic beauty. There are several stormwater channels which feeds the lake during monsoon seasons.

There are large fluctuations in quantity as well as quality of stormwater runoff (Zhang et al., 2010; Wei et al., 2010), posing a challenge to its proper treatment. Coagulation and flocculation process are used for treatment of surface water. Ballasted Sand Flocculation (BSF) is a new physico-chemical treatment process that uses continuously recycled media (sand) along with coagulant and coagulant aid to improve the settling properties of the flocs formed during the process through improved floc bridging and increases the density of flocs (Plum et al., 1998; Landon et al., 2006; Kumar et al., 2016). As a result, the BSF processes require less land footprint for achieving similar quality as is achieved through conventional coagulation-flocculation. BSF has been successfully applied to both water and wastewater treatments in Europe, USA and Australia, however, this technique have not been employed for stormwater runoff treatment in India. In the present study, a pilot plant of capacity 1 MLD was installed near the Naina devi drain (Nainital Lake's catchment) for runoff treatment of the drain. Micro-sand (MS) ballasted jar tests were conducted in the lab for the optimization of coagulant and coagulant aid and the optimized chemicals were applied for treatment through full scale pilot unit. The jar test results were also compared with the field scale application of the BSF unit at Nainital.

## METHODOLOGY

### *Sample collection*

The study site, Nainital lake catchment area, is located around 1,937 m above the mean sea level (MSL), in the foothills of the outer Himalayas. Water samples from Naina devi drain (Fig. 1), a major drain in the lake catchment, were collected. The catchment area of Naina devi drain is 2.46 sq. km. The water samples from site for the high, medium and low rainfall intensities were collected during three sampling campaign in year 2016 and two sampling campaign in year 2017 for comparison of treatment efficiency of full scale plant with lab study. Samples were collected after 20 minutes of rainfall initiation by assuming that runoff from farthest point reaches the drain at outlet. The water samples (40 Litre) from sampling site were brought to the laboratory and MS ballasted jar tests were conducted. The water samples (raw water and settled water) were analysed for turbidity, total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), ortho and total phosphorous (O-P and T-P) and trace metals (Cu, Zn and Pb). All the grab samples were analysed as per Standard Methods (APHA, 2012).

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**Fig. 1: Study site location (a) Google earth view of Nainital Lake and Naina devi drain (b) Pictorial view of Naina devi drain**

***Experimental design***

MS ballasted jar tests were conducted following the procedures of Ding et al., 1999 and Zhu et al., 2007 in transparent 1-L beakers placed on a standard jar test apparatus equipped with an impeller which can reach up to 300 rpm speed. In each beaker, the impeller was lowered in such a way that it reaches near bottom of the beaker, to ensure that the ballasted flocs were maintained in suspension. In the laboratory procedure, stirring of the raw water in the beakers was initiated and coagulant injected at time zero. The pre-weighed micro-sand was introduced after 2 minute along with cationic polyelectrolyte (A 0.01% soluble solution of the polyelectrolyte was prepared by mixing it with distil water using a magnetic stirrer for about an hour). After 2 min of addition of sand and polyelectrolyte, it was allowed for 6 minute maturation. A variable mixing was maintained at 170-180 rpm for coagulation and 40-50 rpm for flocs maturation. After maturation, the flocs were allowed to settle for 6 minutes. Finally, the required amount of clarified water was siphoned from 6 cm below the top surface of water column for analysis.

## RESULTS & DISCUSSION

A total of 5 storm events were sampled during the period of the study for conducting MS ballasted jar tests in triplicate. They are divided into two types based on purposes: first three jar tests (jar test-1, jar test-2 and jar test-3) were conducted for optimizing the chemicals and last two jar tests were done for comparison of field scale application with lab scale experiments. For optimizing the chemicals, the jar tests were conducted corresponding to rainfall intensities 2.5 mm/hr, 10 mm/hr and 38 mm/hr respectively (Table 1). Stormwater runoff is characterized by high turbidity, TSS, COD, BOD and total phosphorous (T-P) as shown in Table 1. The high concentration of pollutants was not resulted from runoff mixed with wastewater only but essentially originates from the erosion of sewer sediments. The pollutants concentration values are less during the events with low rainfall intensity in comparison with high rainfall intensity. The removal efficiency of turbidity, total suspended solids, ortho-phosphorous, total phosphorous, COD, BOD, Zn, Cu and Pb ranges from 98-99%, 94-99 %, 70-90%, 83-94%, 62-82%, 56-78%, 58-66%, 63-66% and 60-78%, respectively (Table 1 and Fig. 2) at optimized dosage of alum and polyelectrolyte. The procedure of optimization of chemicals is described in subsequent paragraphs.

***Optimization of alum dose***

The rapid mix time for coagulation was fixed for 2 minutes and alum dose was varied between 5-30, 10-60 and 40-120 mg/l for first, second and third jar test conducted for different rainfall intensities corresponding to different turbidity. After rapid mixing, it was allowed for slow mixing and settling. No polyelectrolyte was added. A graph between alum dose and residual turbidity was plotted (Fig. 3 (a)) and the dose, 20, 40 and 80 mg/l, corresponding to minimum residual turbidity was chosen as optimum coagulant dosages.

***Optimization of polyelectrolyte dose***

The polyelectrolyte dose was varied between 0.1-1.2 mg/l for first and second jar test and 0.3-1.5 mg/l for third jar test at fixed coagulant dose of 20, 40 and 80 mg/l. polyelectrolyte was added after alum coagulation and rapidly mixed for an additional 2 minutes, followed by slow mixing and settling. The plots of residual turbidity with polyelectrolyte dose at fixed coagulant dose are illustrated in Fig. 3(b). The polyelectrolyte dose of 0.5, 0.7 and 1.2 mg/l was observed to be most effective in removing turbidity and thus chosen as optimum dosages.

**Table 1: Performance of the Jar tests conducted for low, medium and high rainfall intensity**

| | Turbidity (NTU) | TSS (mg/l) | $PO_4$-P (mg/l) | T-P (mg/l) | COD (mg/l) | BOD (mg/l) | Zn (µg/l) | Cu (µg/l) | Pb (µg/l) |
|---|---|---|---|---|---|---|---|---|---|
| **Jar test-1 (sampling date: 2-7-16); Rainfall intensity (low)- 2.5 mm/hr** (Optimized dose: Alum- 20 mg/l, Polyelectrolyte- 0.3 mg/l) | | | | | | | | | |
| Before | 52 | 70 | 0.14 | 0.48 | 52 | 24 | 308 | 32 | 18 |
| After | 1.1 | 4 | 0.04 | 0.08 | 18 | 7 | 130 | 11 | 7 |
| **Jar test-2 (sampling date: 11-7-16); Rainfall intensity (medium) -10 mm/hr** (Optimized dose: Alum- 40 mg/l, Polyelectrolyte - 0.5 mg/l) | | | | | | | | | |
| Before | 204 | 314 | 0.2 | 0.7 | 185 | 90 | 552 | 40 | 25 |
| After | 1.7 | 6 | 0.06 | 0.1 | 70 | 40 | 185 | 15 | 10 |
| **Jar test-3 (date: 25-7-16); Rainfall intensity (high) -38 mm/hr** (Optimized dose: Alum- 80 mg/l, Polyelectrolyte - 1.2 mg/l) | | | | | | | | | |
| Before | 698 | 840 | 0.4 | 1.4 | 440 | 225 | 720 | 52 | 65 |
| After | 2.4 | 10 | 0.04 | 0.08 | 80 | 50 | 270 | 18 | 14 |

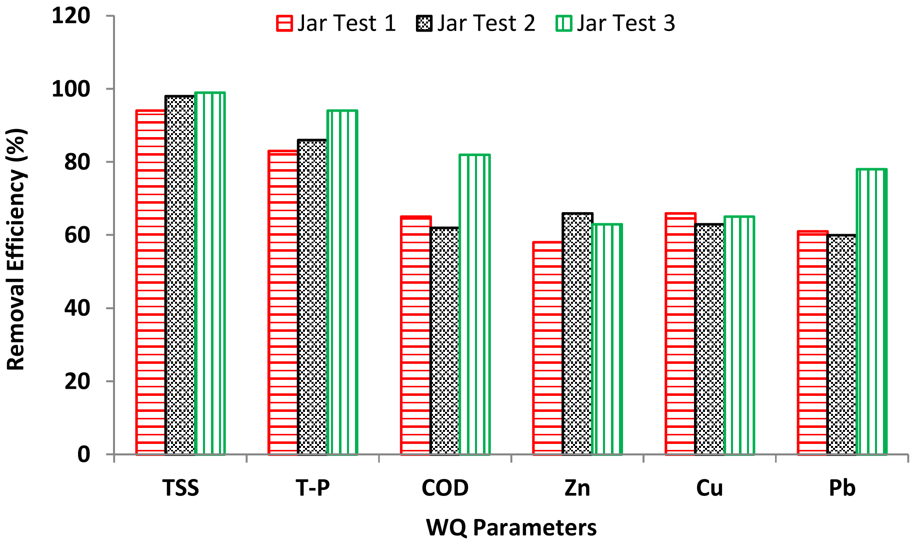


**Fig. 2: Removal efficiency of pollutants at optimized dosage of coagulant and coagulant aid**

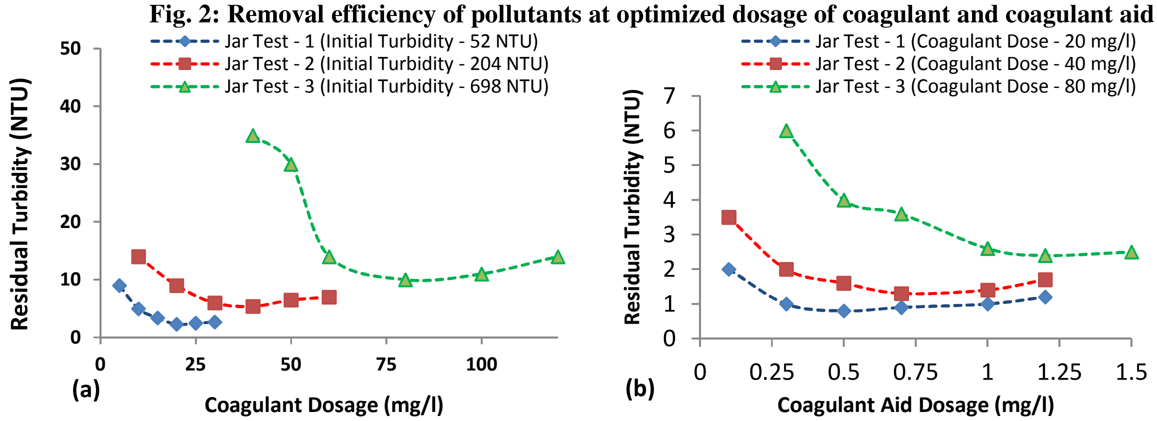


**Fig. 3: (a) The plot between residual turbidity and coagulant dosage (b) Plot between residual turbidity and coagulant aid dosage**

***Selection of sand dose***

Many researchers (Zhu et al., 2007; Gasperi et al., 2012; Imassuen et al. 2004) have reported that the performance of the BSF process are effective when sand sizes are in the range of 75-250 µm and thus in the present study the micro-sand size was chosen 130 µm. The sand applied was 10 gm/l for the experiment.

***Effect of MS concentration***

Past studies have indicated that a significant amount of pollutant is associated with colloidal and larger particles. The colloidal particles adsorb heavy metals, organic matter and water borne micro-organism, therefore, removal of these particle are important in treatment process. In the BSF process, particles coagulated with micro-sand are removed by

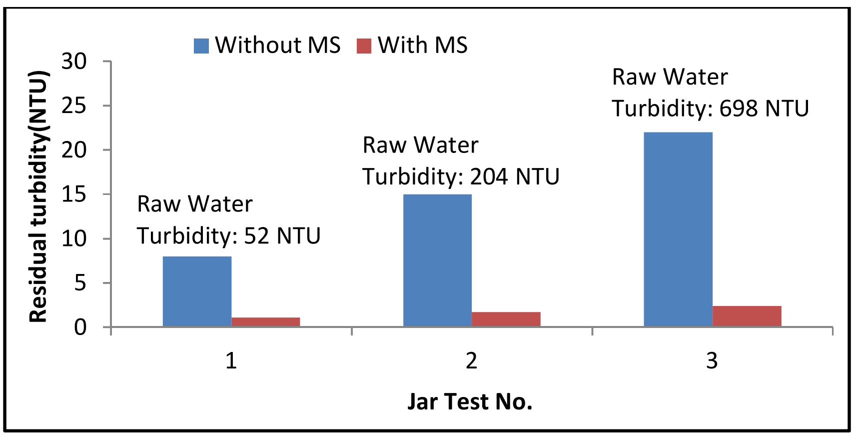


**Fig. 4: Performance of jar test with and without micro-sand**

high rate sedimentation processes. The micro-sand play a vital role in enhancing settling properties as it increases the surface area and density. The jar tests were conducted with and without micro-sand with optimum dosages of alum and polyelectrolyte to study the effect of ballast material. The results revealed that the residual turbidity is very less (< 2.5 NTU) in comparison with jar test performed without MS with 6 minutes of settling (Fig. 4). It may be concluded that the addition of MS significantly improved the suspended solids settleability and its removal from the runoff water.

***Comparison of lab scale and field scale ballasted flocculation***

To evaluate the applicability of the jar-test method for field scale ballasted flocculation treatment unit, the modified jar test procedure was applied for two storm events occurred in year 2017. The laboratory method (MS ballasted jar tests) can not exactly replicate the full scale as many factors are different: impeller design, shape of beaker, lamella in the clarifier, upflow velocity, etc. The full-scale hydraulics and dynamics cannot be reproduced in a jar. However, the same dosages and contact times applied at the full scale plant were accurately replicated in the laboratory. The pictorial view of lab scale method (jar apparatus) and full scale pilot plant is shown in Fig. 5. The characteristics of the influent and effluent of pilot plant and settled water of jar tests have been presented in Table 2. The result revealed that there is a good consistency between lab and field-scale results in terms of removal of turbidity, TSS, T-P, COD, BOD and trace metals of the settled water.

## CONCLUSION

The study was performed for deciding optimal dosage of coagulant and coagulant aid with effect of micro-sand on treatment efficiency by conducting jar tests for different rain events. The performance of jar tests were also compared with field scale BSF technology, applied for stormwater runoff treatment at Nainital, India. The results of the study clearly

**Table 2: Influent and effluent characteristics with operational parameters of field scale application with settled water of jar test**

| | **Turbidity** (NTU) | **TSS** (mg/l) | **$PO_4$-P** (mg/l) | **T-P** (mg/l) | **COD** (mg/l) | **BOD** (mg/l) | **Zn** (mg/l) | **Cu** (mg/l) | **Pb** (mg/l) |
|---|---|---|---|---|---|---|---|---|---|
| **Plant operation date:** 18-6-2017 **Operational parameters:** Coagulant dose- 70 mg/l; Coagulant aid dose- 1 mg/l; Micro-sand effective size & dose: 130 µm, 8 gm/l; Hydraulic loading rate – 30 $m^3/m^2/hr$ | | | | | | | | | |
| Inlet | 572 | 795 | 0.7 | 1.1 | 385 | 155 | 740 | 24 | 39 |
| Outlet | 3.5 | 18 | 0.07 | 0.1 | 86 | 52 | 289 | 11 | 12 |
| Jar test | 2.3 | 11 | 0.04 | 0.08 | 70 | 50 | 220 | 8 | 12 |
| **Plant operation date:** 24-7-2017 **Operational parameters:** Coagulant dose- 25 mg/l; Coagulant aid dose- 0.5 mg/l; Micro-sand effective size & dose: 130 µm, 8 gm/l; Hydraulic loading rate – 30 $m^3/m^2/hr$ | | | | | | | | | |
| Inlet | 92 | 110 | 0.14 | 0.35 | 75 | 45 | 545 | 28 | 15 |
| Outlet | 2.1 | 8 | 0.03 | 0.04 | 33 | 18 | 126 | 9 | 5 |
| Jar test | 1.4 | 5 | 0.02 | 0.04 | 30 | 16 | 114 | 10 | 4 |


**Fig. 5: Pictorial view of Jar apparatus with (a) Raw water (b) Settled water (c) Pilot Plant installed at Nainital**

demonstrate that increase in the dosage of coagulant and coagulant aid is desired with increase in the rainfall intensity to achieve similar treatment efficiency. The optimized alum dosage of 20-80 mg/l as a primary coagulant and cationic polyelectrolyte with dosage of 0.3 -1.2 mg/l as a coagulant aid, the process was found to be most effective. The micro-sand ballasted jar tests yielded better results than the jar tests performed without sand. The MS ballasted jar-test procedure was able to predict the performance of the field scale BSF unit with good accuracy in terms of treated water quality. The removal efficiency of turbidity, total suspended solids, ortho-phosphorous, total phosphorous, COD, BOD, Zn, Cu and Pb were found to be more than 98%, 93%, 79%, 89%, 56%, 60%, 61%, 54% and 67% respectively for both lab and field scale application of BSF technology.

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