Riverbed Filtration Clogging at Wohler on the Russian River, Sonoma County, California

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ABSTRACT

Riverbed Filtration Systems (RBFs) are low cost and sustainable alternatives to traditional drinking water treatments. RBFs naturally provide water by inducing surface water to flow through riverbed soils to pumping wells in the adjacent aquifer. As water percolates through the riverbed, bed sediments and aquifer material act as natural filters to remove contaminants. Despite the advantages of RBFs, riverbed clogging is a challenge that prevents optimal filtration. The RBF on the Russian River in Sonoma County, California (operated by the Sonoma County Water Agency (SCWA)) provides a study site to examine this challenge. In this study part of Lawrence Berkeley National Laboratory's RBF research, I determined if clogging of the Russian River RBF is due to sedimentation (an increase in the presence of smaller particles on the riverbed) during the dry season when SCWA erects an inflatable dam. Using cryogenic coring to retain undisturbed riverbed samples, I collected samples during May, September, and November to evaluate seasonal and spatial grain size distribution changes. I then performed sieve analysis to determine grain size distributions, used the Microsoft Excel plug-in GRADISTAT to calculate sample statistics, and calculated hydraulic conductivity. Overall, the grain size distribution plots did not show a fining over the study period except for the top sections of the riverbed. These results do not conclude that sedimentation of fines is the primary clogging mechanism of the Russian River RBF. Other clogging dynamics must play a role during the summer dry months.

KEYWORDS

Hydraulic conductivity, water supply, cryogenic coring, seasonal sedimentation, grain size distribution

INTRODUCTION

Riverbed Filtration Systems (RBFs) are low cost and sustainable alternatives to traditional drinking water treatment technologies that have the potential to supply water to 120 million people in the United States (Ray 2001). RBF is a natural filtration process that utilizes sustainable chemical, biological, and physical filtering processes to produce the potable water (Ray et al. 2005). They have low energy, resources, and maintenance requirements, which minimizes greenhouse gas (GHG) emissions. In addition, RBFs generate no waste streams because the systems use no chemicals during the filtration process. Researchers know of minimal environmental impacts from system construction and operation (collector wells are located in the aquifer and do not obstruct fish and sensitive habitats). RBF systems provide drinking water through a variety of filtering processes in the surface water/aquifer interface known as the *hyporheic zone.* These filtering processes are induced by the pumping in the RBF, which sends potable water from the aquifer to collector wells.

The RBF process naturally produces drinking water by inducing river water to flow through riverbed soils to pumping wells in the adjacent aquifer (Figure 1). Pumping wells that induce filtration from surface water to the aquifer (Jaramillo 2012) are crucial to RBF efficiency**.** The water pumping generates a hydraulic pressure gradient and induces the flow of the surface water through the riverbed to the aquifer (known as "induced filtration/ recharge") (Hubbs 2006). As the water percolates through the riverbed soils, the bed sediments and aquifer material act as natural filters for removing various contaminants from surface water (Ray et al. 2005). RBFs remove contaminants such as organics, microbiological pathogens, and particles from surface water which sufficiently filters the water and minimizes the need for additional chemicals (Ray et al. 2002).

The composition and grain size of riverbed materials within the hyporheic zone controls the permeability and therefore strongly influences the hydraulic connection between the river and groundwater (Jaramillo 2012, Zhang et al. 2011). Variation in riverbed grain size is crucial for the effective RBF functioning; mixed grain materials exhibit high hydraulic conductivity and provide better natural infiltration (Ray et al. 2005). RBF performance depends on maximizing conditions for drinking water production, which includes minimizing filtration obstacles that are frequently encountered by the systems.

Although potential exists for RBF systems to provide sustainable, high-quality water, unique challenges can prevent optimal infiltration (Grischek et al. 2003, Schubert 2006b, Jaramillo 2012). Clogging of the riverbed, for example, can potentially affect the filtration process (Schubert 2006b, Goldschneider et al. 2007, Jaramillo 2012). The dynamic process of riverbed clogging decreases infiltration effectiveness; it has various forms and causes, including sedimentation of fine particles in the hyporheic zone, biofilms that block the aquifer pores, and geochemical reactions (Caldwell 2006, Jaramillo 2012, Brunner et al. 2011). The clogging is detrimental to water filtration system effectiveness because fine sediments reduce hydraulic conductivity by inhibiting the percolation of water through the river bed's porous media. This decreases the flow velocity and quantity of water passing from the river to the aquifer (Banzhaf et al. 2011, Caldwell 2006, Schubert 2006b, Ray et al. 2005). Conductivity of the riverbed controls the quantity of water that is filtered (Caldwell 2006), and reduced permeability from clogging is a common problem.

The Russian River in Sonoma County, California provides a study site to examine the unique set of challenges facing RBFs because its current RBF system has unknown limitations inhibiting optimal filtration. The Russian River supplies drinking water to 600,000 people in Sonoma and Marin Counties and runs through Mendocino County and westwards to the Pacific Ocean. Sonoma County Water Agency, who manages the RBF, observes riverbed clogging at the RBF system along the Russian River, specifically at the Wohler site during the summer months when an inflatable dam is erected. The causes of the clogging are unknown, and if not rectified will result in loss of long-term yield (Caldwell 2006, Zhang et al. 2011).

This study will determine the grain size distribution of the riverbed at the Wohler site to determine if sedimentation, an increase in the presence of smaller particles in the hyporheic zone, is the main clogging mechanism of the RBF system. In particular, I will determine the grain size distribution of riverbed sediment at Wohler, and its effects on hydraulic conductivity. An increase in fine particles at Wohler during the dry season when an inflatable dam is erected would decrease the hydraulic conductivity of the river, and lead to decreased riverbed permeability and clogging. Hydraulic conductivity and grain size are correlated because of the increase in fine sediments blocking the porous material and impeding water filtration. This would imply that sedimentation is the primary clogging mechanism of the RBF.

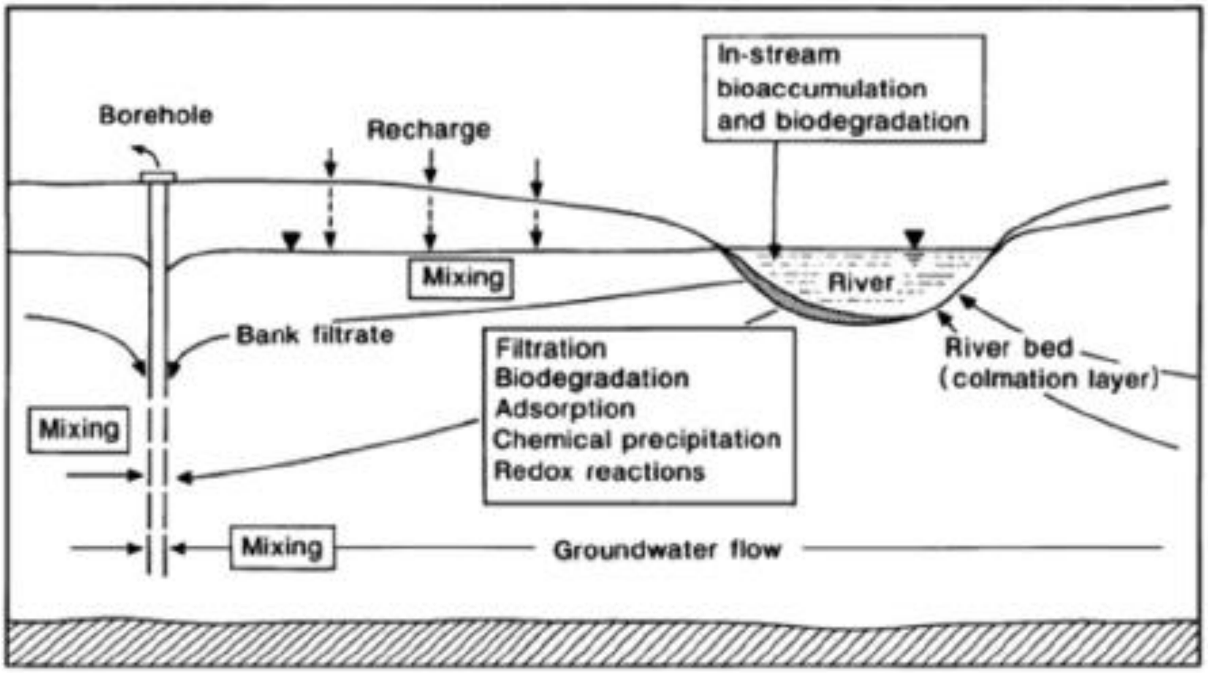

Fig 1. A riverbed filtration scheme (Jaramillo 2012).

METHODS

Study site

I conducted the study along the Russian River in Sonoma County, California at the Wohler Site (Figure 2). The Russian River originates in Mendocino County, flows south into Sonoma County, and then westwards to the Pacific Ocean. Sonoma County Water Agency (SCWA) operates an RBF system there, which supplies drinking water to 600,000 people in Sonoma and Marin counties. The system comprises six horizontal collector wells and seven vertical wells with a maximum total capacity of more than 92, in addition to about 20 million gallons/day standby capacity (Zhang et al. 2011). They are approximately 15 feet in diameter and 55 feet below the surface of the streambed and they extract groundwater from the aquifer below through vertical pumps. The Wohler site contains two of these wells, approximately 75m apart. Downstream of the Wohler site an inflatable dam is erected during the dry season to increase water level to enhance river infiltration and aquifer recharge for the production of drinking water (Zhang et al. 2011). Sonoma County Water Agency lowers the dam in the fall when water demand decreases and the river flow increases. The erection of the inflatable dam results in lower flow velocity during the summer months.

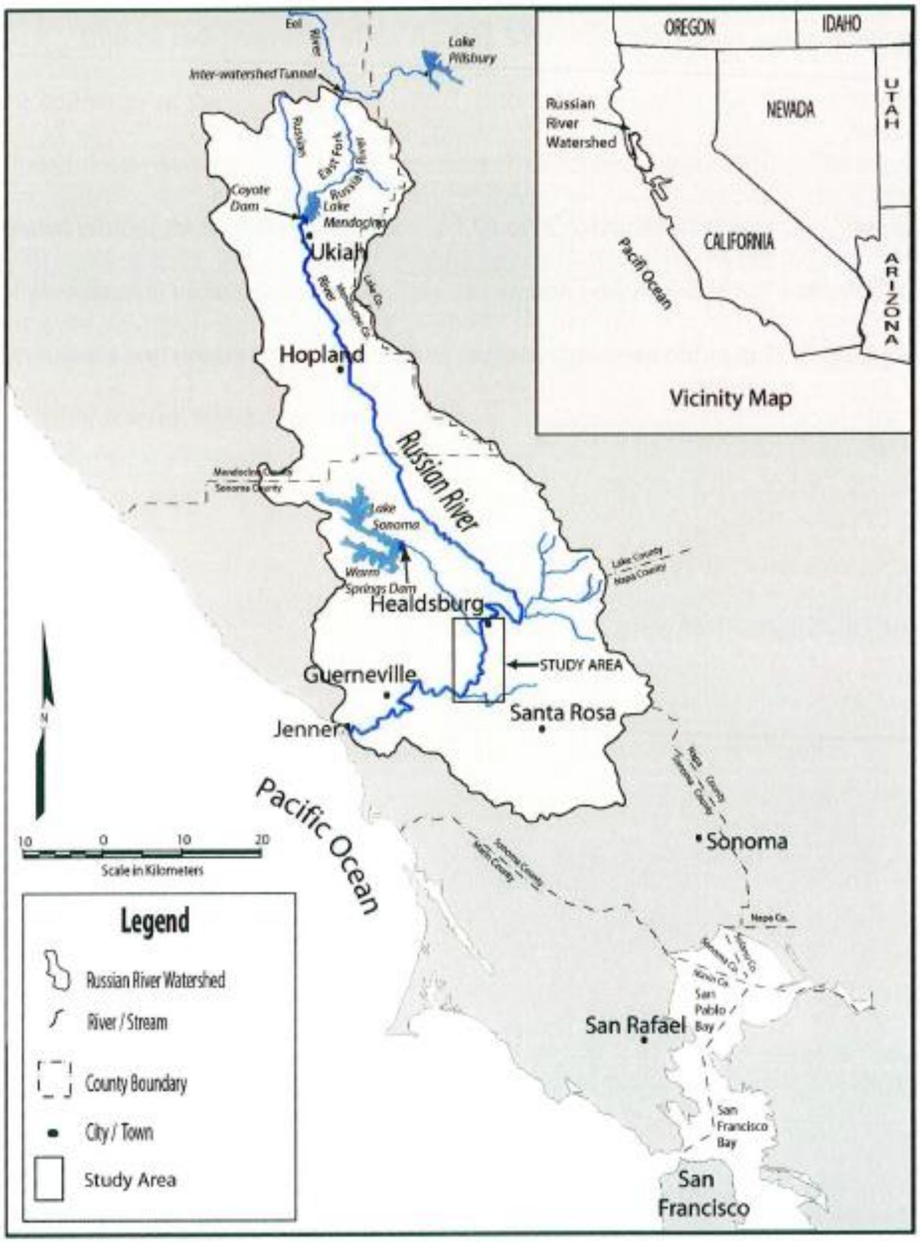

Fig 2. **Map of the Russian River and Wohler study site** (Gorman 2004).

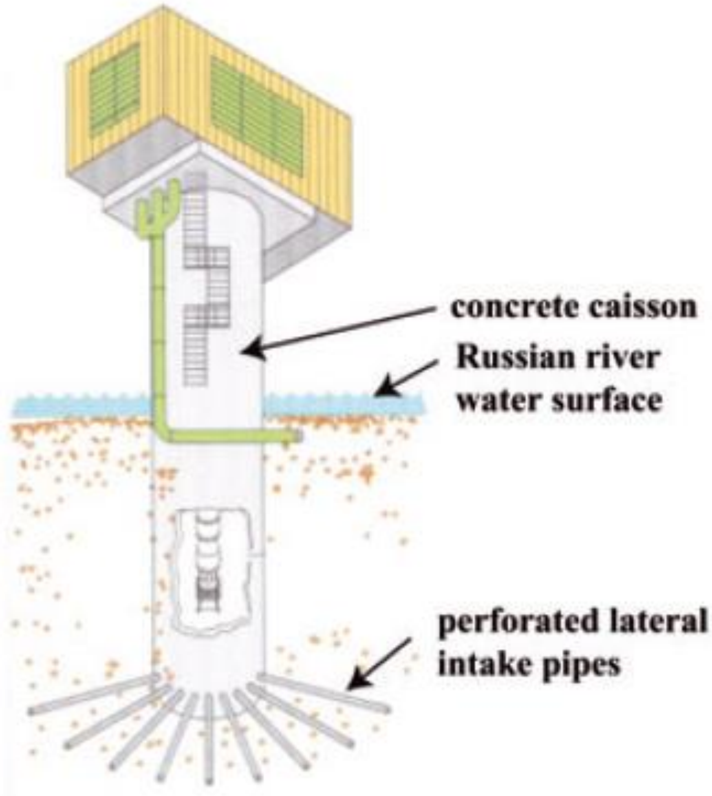

Fig 3. **Schematic of a collector well at the Wohler site**. Each collector well consists of 9 to 12 horizontal laterals extending in a radial direction from a caisson beneath the river (Zhang et al. 2011).

Data collection

I collected one sample from six locations at the Wohler site using the cryocore method during May, September, and November (18 samples total) to evaluate seasonal and spatial clogging fluctuations along the riverbed. The six locations are chosen to evaluate the grain size distribution changes on the riverbed along the longitudinal profile and the cross section. I used a cryogenic freezing method to collect undisturbed sediment core samples from the riverbed at the six locations. I nailed an approximately two-foot long copper pipe into the riverbed. Nitrogen blew into the pipe to freeze the surrounding riverbed material. The sediment around the pipe froze and we manually removed it from the riverbed. We immediately transferred the core to a chest containing liquid nitrogen so the samples could remain frozen and undisturbed. We transferred the samples to the laboratory in the chest and then stored them in a freezer until analysis.

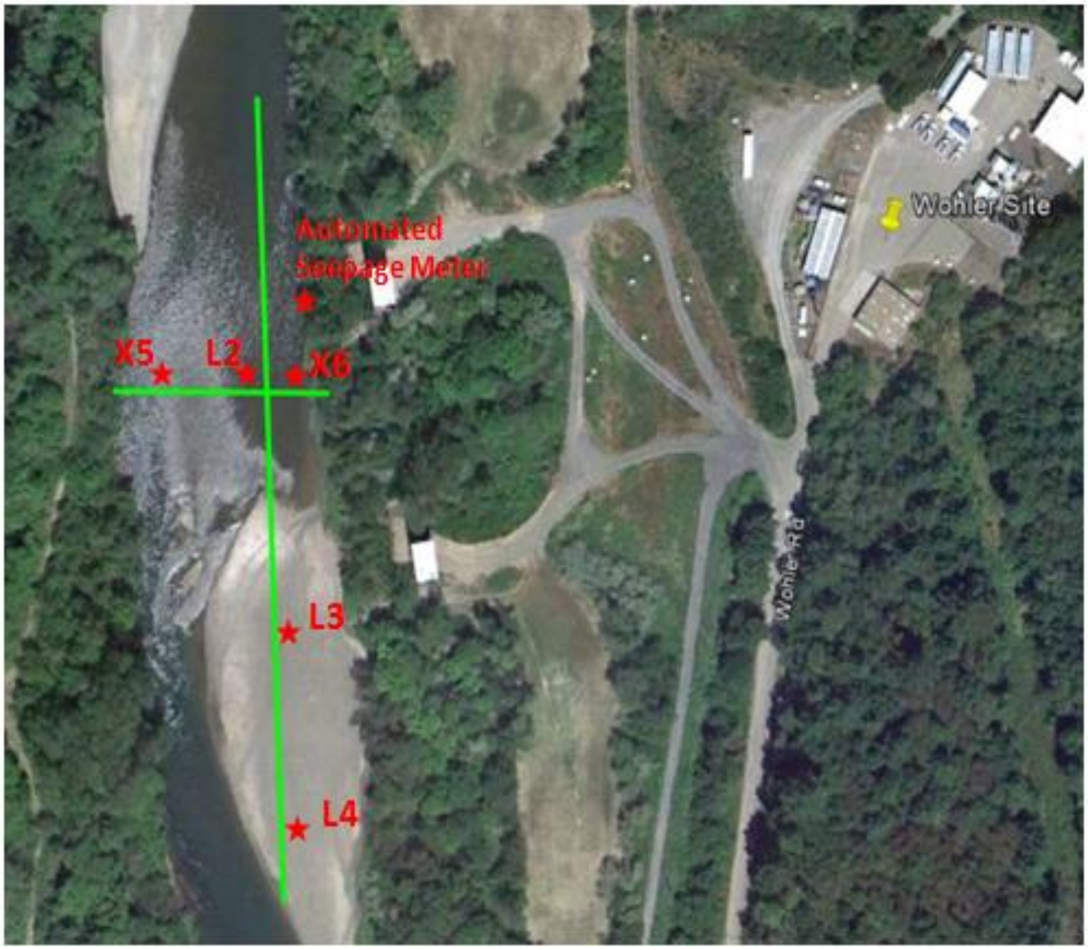

Fig 4. The Wohler site. The red stars indicate the six sample locations. I chose the cross section and longitudinal locations to evaluate how the riverbed clogging changes spatially.

Analysis of core samples

I transferred the core samples from the freezer to the laboratory, where I segmented each core based on length (i.e., depth into the riverbed) to assess how the grain size distribution changes through the depth of the riverbed (e.g. fine sediments are more likely to settle at the top of the riverbed from low-velocity seasonal fluctuations). The segments began at 0cm, indicating the top of the riverbed, and continued to 5-10cm, 10-20cm, and 20+ cm of the length of the core. I weighed the wet samples and then placed them in an oven to evaporate the remaining water from the sediment. Once evaporated, I recorded the dry weight of each sample.

Fig 5. A frozen core sample before it was cut into segments.

I used sieve analysis according to ASTM standard D 422 "Standard Test Method for Particle Size Analysis of Soils" to determine the distribution of particle sizes within the riverbed. To determine size fractions, we used a mechanical sieve machine with openings ranging in size from 9.5mm to 0.07366mm (Appendix A). Eighteen sieves were used because of the wide range of particle sizes observed in the Russian River (Gorman 2004). I sieved most samples for 5 minutes, but the finer grains (0.24892mm to 0.07366mm) were sieved for ten minutes to improve accuracy. I weighed each sieve after the mechanical sieving process to see how much sediment was retained.

I used the Microsoft Excel plug-in GRADISTAT V 8.0 to calculate sample statistics for each of the eighteen core samples. GRADISTAT is a plug-in created specifically for analysis of grain size distribution of sieve analysis data. GRADISTAT computed the mean, mode(s), sorting (standard deviation), skewness, kurtosis, D_{10}, and D_{50}. The D values represent the percentage of the grain sample finer than a given diameter (e.g. when D_{35} equals .5-mm, 35% of the sample weight has grain sizes less than .5-mm).

Data analysis

To evaluate how the distributions changed according to location and depth within the riverbed, I used sieve results to plot grain size distribution curves for each sample. I used Microsoft Excel to plot the data and generate graphs. I plotted percent finer by mass on a normal scale and grain size on a logarithmic scale because sediments tend to have a normal distribution of the logarithms of grain diameter (Gorman 2004). Grain size distributions with more fine sediments are left-dominated, indicating a greater percentage of the sample with a smaller grain diameter.

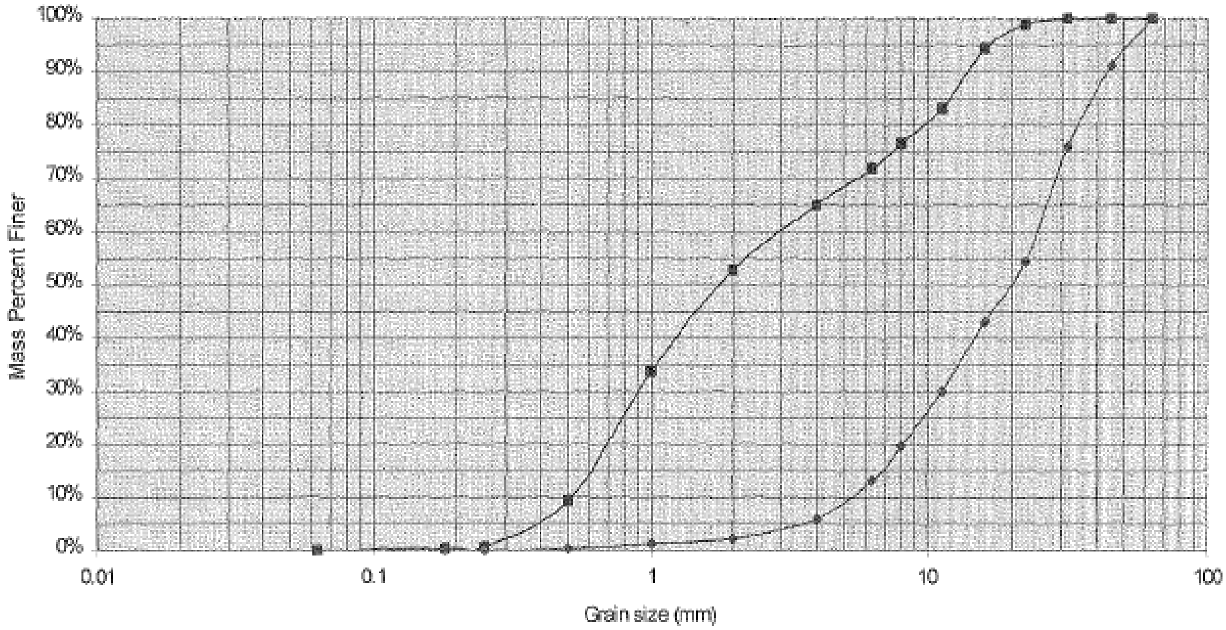

Fig 6. A Particle-Size Distribution plot (Gorman 2004). The plot on the right displays a higher percentage of coarser grain sizes, whereas the plot on the left has more fine sediments.

I calculated hydraulic conductivity of the sample to determine how well fluid passes through the pore spaces of the riverbed. Hydraulic conductivity is one of the most important characteristics of water-bearing formations due to its significant influence on flow patterns (Alyamani and Sen 1993). The hydraulic conductivity of soil is necessary for modeling water flow in the soil, and transportation of water-soluble pollutants in the soil (Odong 2007). A large hydraulic conductivity value indicates a high permeability and filtration. Finer sediments exhibit low conductivities because water cannot filter as well through the pore spaces. To calculate hydraulic conductivity, I used the statistical parameters of each sample (Equation 1).

Equation 1. Kozeny-Carman Equation used to calculate hydraulic conductivity**.**

$$K = \frac{g}{v} \times 8.3 \times 10^{-3} \left[\frac{n^3}{(1-n)^2} \right] d_{10}^2$$

Where *K*= hydraulic conductivity, *g*= acceleration due to gravity, *v*= kinematic viscosity, *n*= porosity function, and d_{10} and d_{60} represent grain diameter in (mm) for which 60% and 10% of the sample respectively, are finer than (Odong 2007).

RESULTS

Sieve analysis results

The results from GRADISTAT show that the particle size distributions of the sediment core samples did not change drastically from May to November. The sediment distributions are similar with depth into the riverbed and between sample locations (Appendix B).

Grain size distribution plots

A visual inspection of the grain size distribution plots did not show an overall trend in the grain size distributions between the May to November samples. There is not a definitive variation in the plots or an obvious coarsening (shift to the right), or fining (shift to the left) between May to November. The grain size distribution plots for all three months are similarly distributed; they do not show an evident deviation in depth or between sampling locations (Figure 7, 8, 9).

However, a closer examination of a comparison between the top sections of the riverbed (0-5cm depth) from May to November does show a visible increase in the percentage of the finest particle sizes (Figure 10). The grain size distribution plots shift left (from May to November) in the bottom of the figure, which corresponds to an increase percentage of the fine particle sizes on the top of the riverbed.

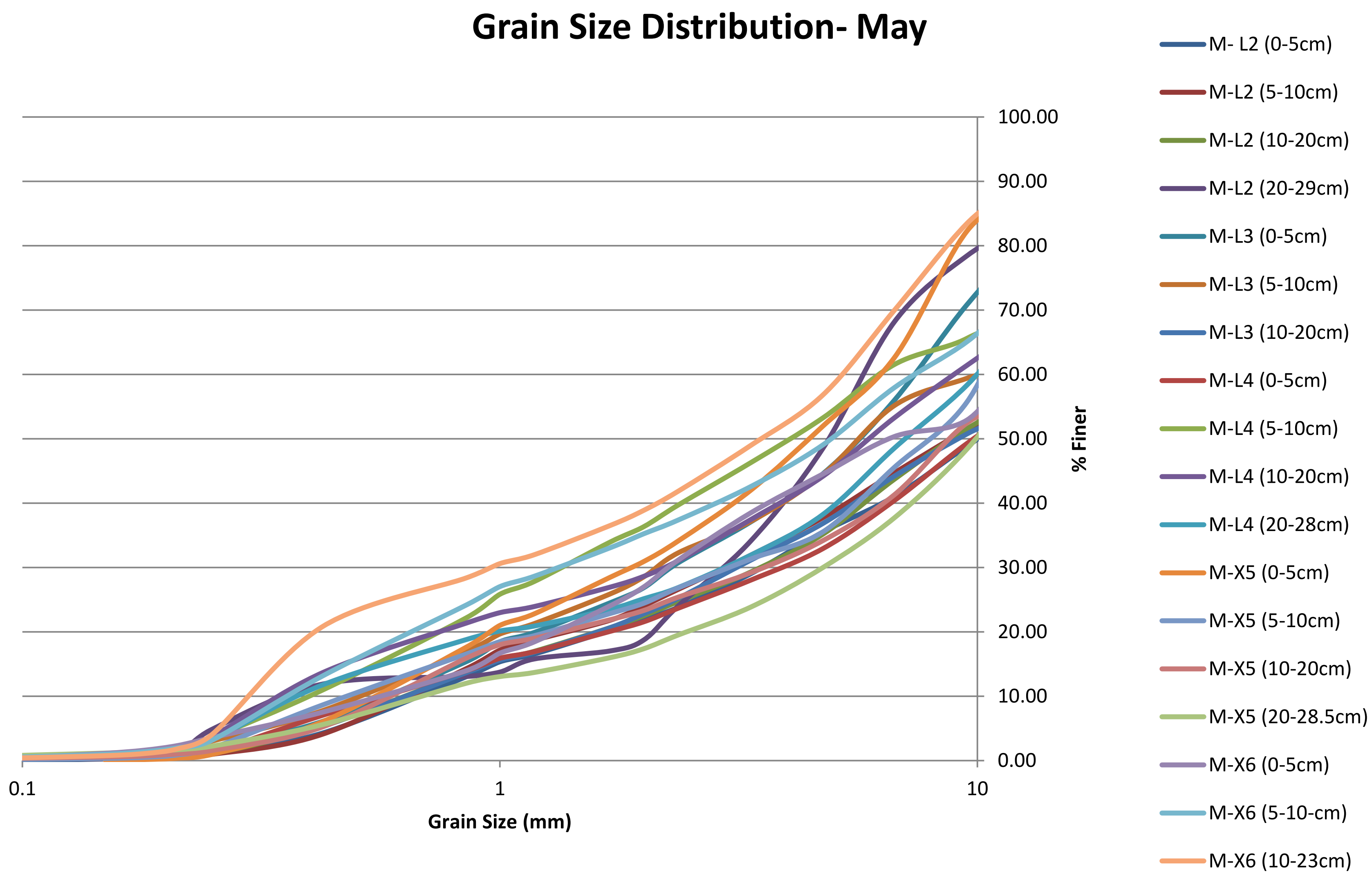

Fig 7. Grain Size Distribution Plots of May samples.

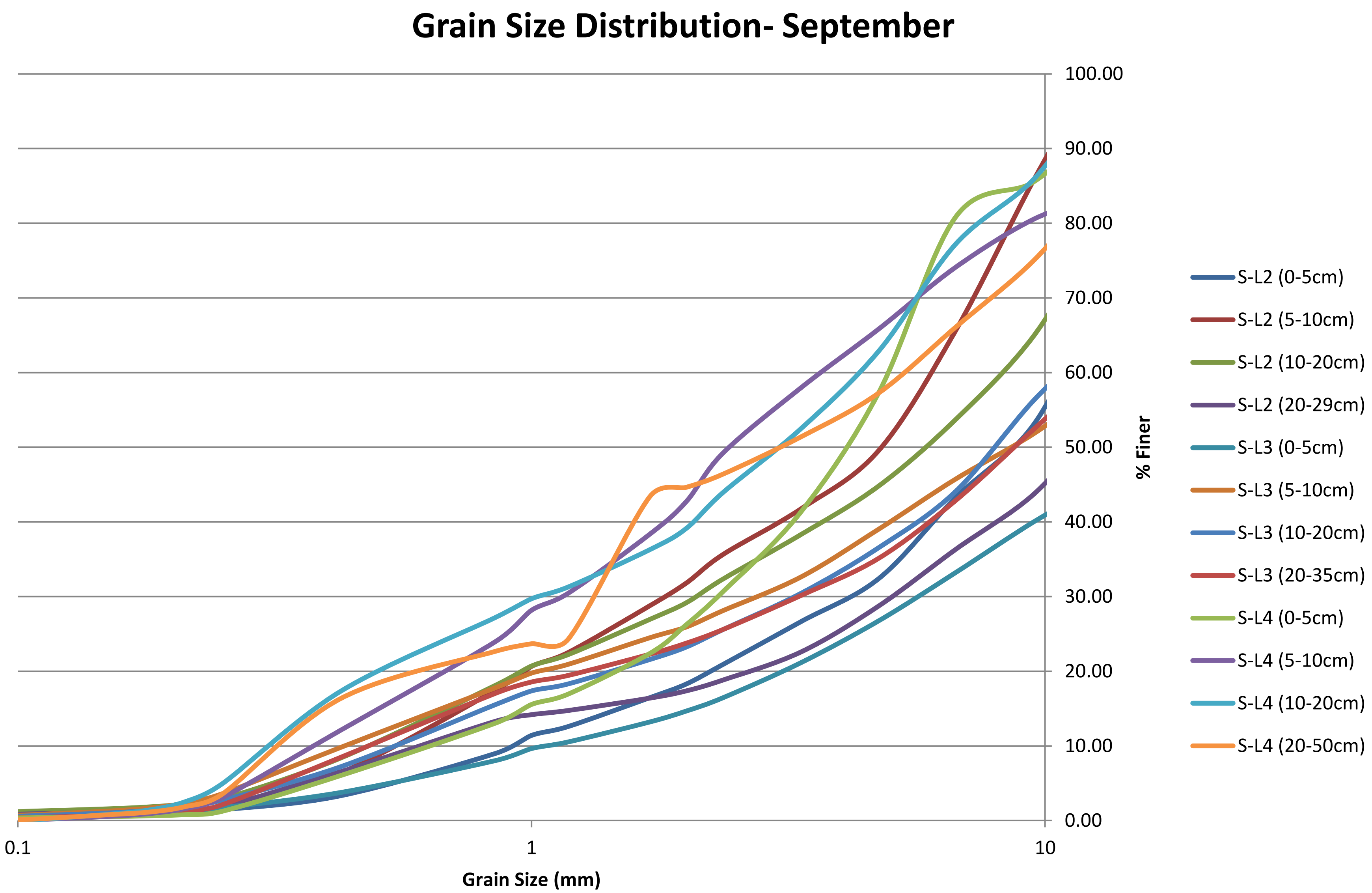

Fig 8. Grain Size Distribution Plots of September samples.

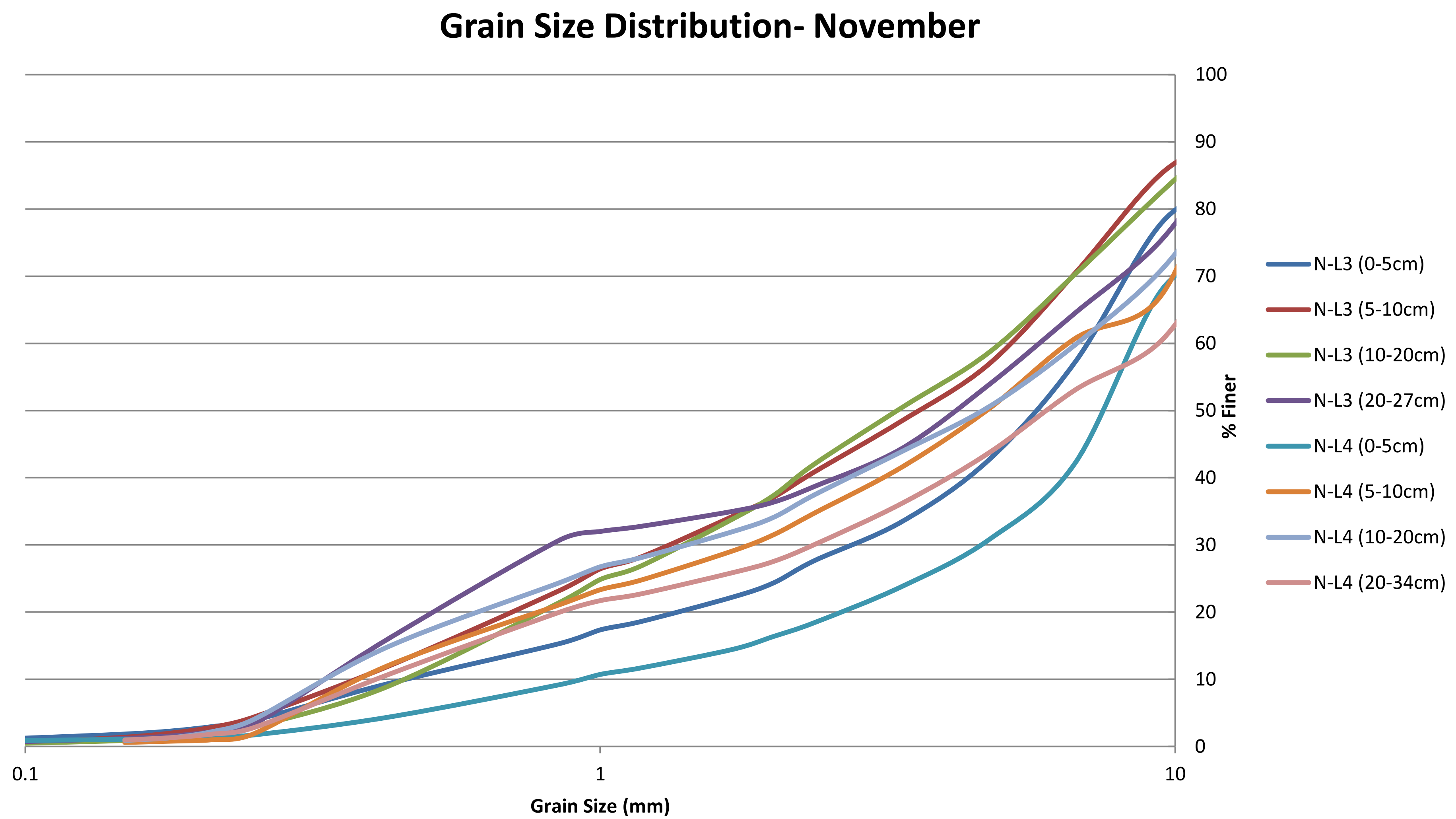

Fig 9. Grain Size Distribution Plots of November samples.

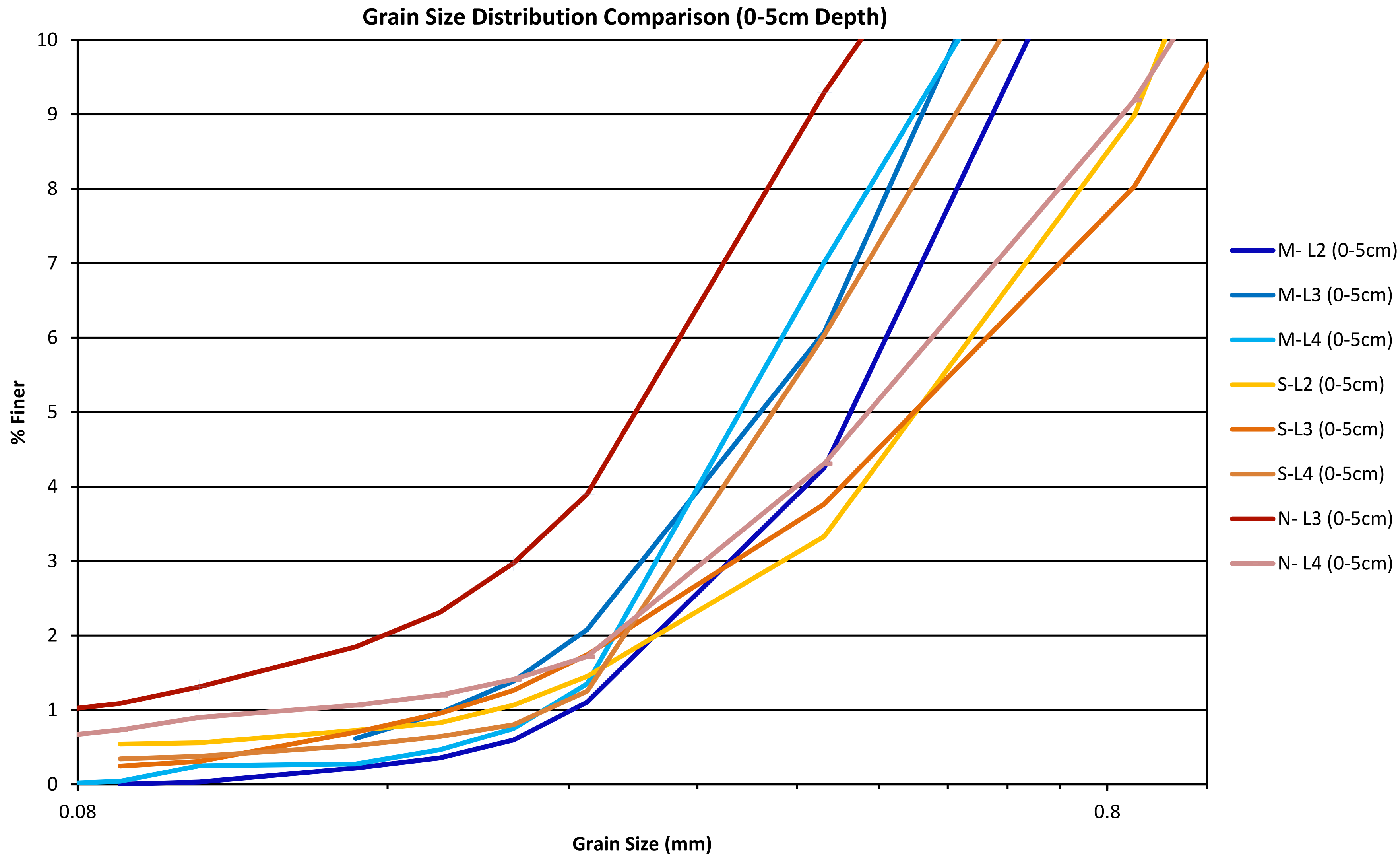

Fig 10. Grain Size Distribution Plot of the top section of the riverbed (0-5cm) for May and September, and November. There is an increase in fine particle sizes from May to November (plots shift to the left from May to November).

Hydraulic conductivity calculations

Hydraulic conductivity values increase from May to September, and suddenly surge in the November samples (Figure 11). The mean K increased over the study period, from 55.58 m/day in May to 91.66 m/day in September, and 76.78 m/day in November (Table 1).

Table 1. Hydraulic Conductivity Values for May, September, and November. (meters/day)

Depth	Sample	May	Sept	Nov
0-5	L2	104.92	227.72	0.00
0-5	L3	83.31	202.21	41.28
0-5	L4	63.35	185.30	362.48
5-10	L2	77.42	141.46	0.00
5-10	L3	56.69	31.27	39.43
5-10	L4	39.60	38.95	32.68
10-20	L2	75.80	58.66	0.00
10-20	L3	76.70	17.65	52.45
10-20	L4	26.23	105.43	24.77
20-30	L2	33.92	70.59	0.00
20-30	L3	0.00	0.00	22.49
20-30	L4	29.12	20.68	38.68
	Mean (m/day)	**55.58**	**91.66**	**76.78**

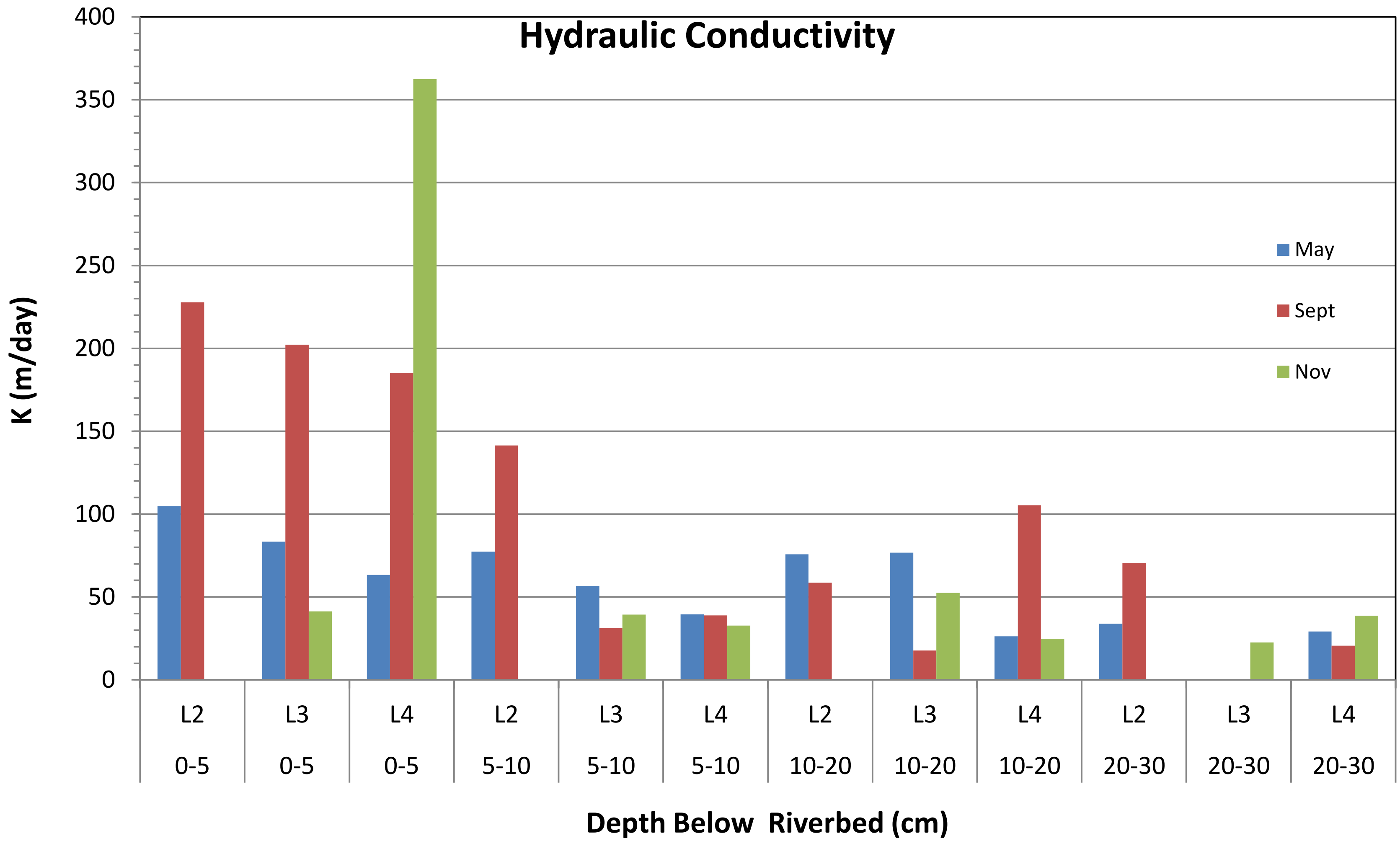

Fig 11. Hydraulic Conductivity for May, September, and November samples (Ulrich et al. 2013 in preparation).

DISCUSSION

The results from this study provide inconclusive evidence with respect to sedimentation as the main clogging mechanism of the riverbed filtration system (RBF) on the Russian River. Results from my sieve analysis and hydraulic conductivity calculations show no visible trends between the May samples (before the inflatable dam is erected) and the November samples (when the inflatable dam is taken down). However there was a slight increase in fine particles in the top layers of the riverbed between the same time period. Although there was an increase in fine particles in the top layer of the riverbed, sedimentation of fine grains on the riverbed is likely not the primary clogging mechanism of the RBF. The results suggest additional clogging mechanisms, such as a biofilm, varying river flow conditions and suspended load, or the direction of the hydraulic gradient of the seepage flow (Schalchili 1992).

Grain size distribution

The overall grain size distributions over the study period are similar, which differs from our expectation that we would see a large increase in fine particles at the top of the riverbed between May and November (Hubbs 2006, Blaschke et al. 2003, Ray et al. 2002). An increase in fines during the dry season would imply that sediment settled on the riverbed when the dam was erected and the river velocity slowed. The fine particles would have blocked the pores between the sediment and decreased filtration in the RBF (Hatch et al. 2010, Zhang et al. 2011, Schalchili 1992, Ray et al. 2002). A look at the top sections of the riverbed samples do align with those studies explaining that as the river velocity slowed, fine sediment accumulated. However, I expected to see a shifting to the left (increase in fines) in the grain size distributions for the other sections of the riverbed over the study period as well. The lack of an overall trend in grain size distributions for all layers and sections of the riverbed could mean that other clogging mechanisms are at play, such as the growth of biotic film blocking filtration, an increased suspended sediment concentration, varying flow velocities, or a hydraulic gradient (Blaschke et al. 2003, Hubbs 2006, Ray et al. 2002).

Hydraulic conductivity implications

The hydraulic conductivity of the riverbed increased and then decreased at Wohler except for a spike in November, suggesting that sedimentation of fine particles in the top section of the riverbed is not enough to decrease the hydraulic conductivity during the dry season. These results are unexpected; I anticipated hydraulic conductivity to decrease from May to November as the fines collected on the riverbed and decreased soil porosity and water percolation (Blaschke et al. 2003, Hatch et al. 2010). The spike in hydraulic conductivity in November could be the result of a sudden increase in the river velocity, temporarily wiping away the fine sediment layer (Hatch et al. 2010), or a scouring of riverbed which could severely alter the hydraulic connection between the river and aquifer (Rosenberry and Pitlick 2009). The varying hydraulic conductivities are similar to Genereux et al. 2008, where alternating erosion and deposition cycles cause the hydraulic conductivity in the upper sections of the streambed to vary up and down but not trend continuously toward higher or lower values.

Streambed hydraulic conductivity is a dynamic attribute, variable in both space and time, and affecting groundwater exchange with streams (Genereux et al. 2008). Heterogeneity in hyporheic exchanges often has been related to channel morphology, and hydraulic conductivity is often temporally variable in fluvial settings (Rosenberry and Pitlick 2009). Thus the spatial and temporal variations in hydraulic conductivity values between the Wohler sample locations potentially imply a temporal restructuring of the riverbed. Evolution of the bed surface in response to fluvial processes results in spatial and temporal changes in hydraulic characteristics of the channel bed, further affecting flow across the sediment-water interface (Rosenberry and Pitlick 2009). As the RBF collector wells pump water from the aquifer**,** the riverbed potentially adjusts or restructures itself to supply the water to the pumps. These riverbed dynamics can be a potential reason why the hydraulic conductivity does not decrease continually over the study period. However, spatial variability in streambed hydraulic conductivity warrants additional study as a potentially important control on temporal variability in fluxes between groundwater and surface water (Genereux et al. 2008). The results from my study only show a portion of the riverbed processes at play on the Russian River because my study uses samples from May, September and November. The hydraulic conductivity pattern for the entire year is unknown, and could paint more complete and accurate picture of the riverbed dynamics.

Implications from LBNL study

My research question focuses only on grain size analysis, but combining my results with the results from LBNL paints a more comprehensive picture of riverbed dynamics to assess conclusions on the RBF clogging mechanisms. Ulrich et al. 2013 (in preparation) used cryocoring, thermal sensing, seepage meters, and sediment traps to investigate and monitor spatiotemporal changes of riverbed permeability subsequent to inundation of the study reach via inflation of a downstream rubber dam. Electrical resistivity tomography (ERT) was also used to image and monitor the development of a pumping induced unsaturated zone beneath the riverbed as a result of decreased riverbed permeability (clogging). In addition to grain size analysis, cryocores were also analyzed for total biomass. The results suggest that riverbed permeability and the development of an unsaturated zone are spatially and temporally variable and influenced by dam stage, pumping rate and transient river pulses. Particularly, riverbed clogging is influenced by biomass development in late season.

Limitations

The limitations of this study may prevent the results from being truly comprehensive and conclusive. Inaccuracy may have occurred during sample collection because the cryogenic method can render imperfect samples. If the core is not completely frozen by the nitrogen when it is transferred out of the riverbed and into the cooler, the sediment at the top of the core can fall back into the river. The result is a core sample that is not completely representative of the true riverbed, as the top section of the sample may be inaccurate. Another source of data collection error is that we could not collect core samples from all the sample locations in September and November because the water level was too high for the cryocore method. This gives an incomplete picture of the riverbed, but we can extrapolate based on the samples we do have. The laboratory sieve analysis also left room for sampling error that can potentially skew the results. These include scale measurement variations, dust and sediment that fell out of sieves while the sample was transferred, and sieves that fell out of sieve shaking machine during the shaking.

Implications for Future Research

The results from this study suggest that additional research is needed to address RBF clogging mechanisms where grain size distribution and hydraulic conductivity vary throughout the year but increase during the dry months when fines are likely to settle on the riverbed. Based on my results, there are additional dynamics that contribute to clogging, such as the creation of a biotic film on the riverbed in late season or an unsaturated zone. RBFs are dynamic systems that change throughout time. Consequently more research needs to be conducted that encompasses the entire spectrum of possible clogging mechanisms. Future research in seasonally-clogged RBFs with groundwater pumping regimes and riverbed seepage variability will help to prevent seasonal clogging at RBFs similar in scope to the Russian River.

Conclusions

There was not a large increase in fine particles at Wohler during the dry season when an inflatable dam is erected, and riverbed hydraulic conductivity varied spatially and temporally. Thus, determination of RBF clogging mechanisms at the Russian River is inconclusive, although sedimentation of fine particles may be a contributing factor. While my results are unexpected, this study leads to broader implications about riverbed fluctuations and suggests room for future research on RBFs with temporal and spatial variations in hydraulic conductivity and grain size distributions. Sonoma County Water Agency can take these results into consideration as they manage the pumping regime of the RBF on the Russian River and monitor river-aquifer interactions and fluctuations over time.

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APPENDIX A: Sieves used in Sieve Analysis

Table A1. Sieves used in sieve analysis.

Sieve #	Opening(mm)
3/8	**9.5**
3	**6.68**
4	**4.699**
5	**4**
6	**3.327**
8	**2.3622**
10	**2**
12	**1.651**
16	**1.18**
18	**1**
20	**0.84074**
35	**0.50038**
40	**0.4191**
60	**0.24892**
70	**0.21082**
80	**0.1778**
100	**0.14732**
170	**0.0889**
200	**0.07366**

APPENDIX B: Gradistat Results

Table B1. GRADISTAT Results for May, September, and November samples.

MAY			
Sample	**D_{10} (mm)**	**D_{60} (mm)**	**Mean** (μm)
X6 (10-23)	0.000266	0.0051	2110
X6 (5-10)	0.000272	0.0043	1950
X6 (0-5)	0.00036	0.0032	905
X5 (20-28.5)	0.000441	0.0078	3060
X5 (10-20)	0.000432	0.0055	2516
X5 (5-10)	0.000297	0.0076	2984
X5 (0-5)	0.000449	0.006	2658
L4 (20-28)	0.000274	0.0059	2598
L4 (10-20)	0.000266	0.0042	1800
L4 (5-10)	0.000287	0.0049	2439
L4 (0-5)	0.000288	0.0049	2294
L3 (10-20)	0.000433	0.0047	2534
L3 (5-10)	0.000295	0.0046	2354
L3 (0-5)	0.000443	0.0053	2439
L2 (20-29)	0.00046	0.0068	3775
L2 (10-20)	0.000431	0.0049	2317
L2 (5-10)	0.000441	0.0049	2543
L2 (0-5)	0.000434	0.0041	20826
SEPTEMBER			
Sample	**D_{10}(mm)**	**D_{60} (mm)**	**Mean** (μm)
L4 20-50	0.000271	0.0037	1934.9
L4 10-20	0.00027	0.0041	2085.3
L4 5-10	0.00028	0.0024	1853.1
L4 0-5	0.000471	0.0048	3364.1
L3 20-35	0.000296	0.0061	2952.6
L3 10-20	0.000432	0.0057	2850.7
L3 5-10	0.000273	0.0039	2340.8
L3 0-5	0.000459	0.0058	3656.7
L2 20-30	0.000294	0.0053	2762.1
L2 10-20	0.000435	0.006	2915.3
L2 5-10	0.000462	0.0058	3552.4
NOVEMBER			
Sample	**D_{10} (mm)**	**D_{60} (mm)**	**Mean** (μm)
L4 (20-34)	0.0002957	0.0095	3080.3
L4 (10-20)	0.0002767	0.0068	2666.3
L4 (5-10)	0.0002896	0.0067	2678.2
L4 (0-5)	0.0009266	0.0085	5478.8
L3 (20-27)	0.0002753	0.0059	2548
L3 (10-20)	0.0004313	0.005	2326.3
L3 (5-10)	0.0002869	0.0051	2307.2
L3 (0-5)	0.0004332	0.007	3739.1