THESIS

MEASURING AND MODELING GEOSMIN REMOVAL FROM HORSETOOTH RESERVOIR WATER BY POWDERED ACTIVATED CARBON FOR SELECTED CONTACT TIMES

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ABSTRACT

MEASURING AND MODELING GEOSMIN REMOVAL FROM HORSETOOTH RESERVOIR WATER BY POWDERED ACTIVATED CARBON FOR SELECTED CONTACT TIMES

Presence of geosmin, an odorous algal metabolite produced by cyanobacteria, has been an issue in drinking waters in Northern Colorado. Geosmin does not pose a health threat; however, it imparts an earthy taste and odor to the finished drinking water even at very low concentrations (5-10 ng/L), resulting in consumer complaints and dissatisfaction. Geosmin cannot be removed by conventional water treatment processes, so further treatment is required to achieve concentrations below detection limits. This study investigated the geosmin removal from the raw water obtained from the Horsetooth Reservoir, in Fort Collins, CO by powdered activated carbon (PAC). The PAC type tested was Hydrodarco-B supplied by Norit Americas Inc. Raw water samples were spiked with stock geosmin solution to obtain concentrations from 10 to 50 ng/L and stock PAC solution to obtain concentrations from 5 to 30 mg/L. Thirteen different geosmin/PAC concentrations were tested for 90 minutes contact time (and up to 6 hours for selected combinations) and the geosmin removal was determined by headspace solid phase microextraction and gas chromatography/mass spectrometry. Results indicated that 50 to 70% removal was achieved for lower doses of geosmin/PAC combinations, and 80 to 97% removal was achieved for higher dose combinations. Most (65%) of the geosmin removal was achieved within the first thirty to forty-five minutes. For 54% of the samples, geosmin concentrations in the treated water were lowered below 4 ng/L, which is a low enough concentration to prevent consumer complaints. Additionally three PAC/geosmin combinations with 8 mg/L TOC were examined and results showed a decrease in geosmin removal by about 10% after 90 minutes. Further analysis with Stat-Ease® Design Expert® (Version 8) was used to predict required PAC dosages for geosmin levels not tested in the study. The model developed by the Design Expert considered the initial geosmin concentration, PAC dosing and contact time, and a simple equation was obtained to predict the remaining geosmin concentrations in the treated water. Results from the statistical analysis fit the data from testing and accurately predicted geosmin removal for concentrations not tested.

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INTRODUCTION

Occurrence of algal blooms and problematic algal metabolites has been an issue for the drinking water utilities in Northern Colorado that get their source water from lakes and reservoirs. Geosmin is one of the most common algal metabolites produced by cyanobacteria and actinomycetes, which imparts an earthy taste and odor to the drinking water at very low concentrations (Gerber and LeChevallier, 1965; Kim et al., 1997; Bruce et al., 2002). Though not harmful to the consumer, geosmin incidents result in customer complaints due to off-flavors, especially in the late summer and early fall when geosmin levels typically peak (McGuire, 1995; Watson, 2004). Because general population can detect geosmin at 4 to 10 ng/L, even the most minute release of geosmin impacts drinking water utilities (Bruce et al., 2002; Omur-Ozbek and Dietrich, 2005). Geosmin removal requires advanced treatment methods as it cannot be removed by the conventional water treatment units. One of the most efficient and cost effective methods is the seasonal use of powdered activated carbon (PAC). Depending on the dosing and contact time, the removal efficiency ranges from 30 to 90 % which may be enough to reduce the geosmin concentrations in the treated water below detection levels (Bruce et al., 2002; Ho et al., 2009).

This research was conducted to provide the City of Fort Collins Water Treatment Facility (FCWTF) with appropriate design parameters, including PAC doses, and contact times, to achieve effective geosmin removal from their source waters. FCWTF obtains its source water from Horsetooth Reservoir and Cache La Poudre River. The FCWTF delivers water to roughly 140,000 residents, currently treating an average of 22 million gallons per day (mgd), with a maximum treatment capacity of 87 mgd, and a finished water storage capacity of 35.5 million gallons. The presence of geosmin in FCWTF finished water is of a special concern as the tap water is used by the local breweries such as Anheuser-Busch, Odell, and New Belgium, and geosmin affects the flavor characteristics of their products. Also FCTWF has a zero tolerance policy for off-flavors in their finished water to prevent consumer complaints and dissatisfaction.

Horsetooth Reservoir is a terminal reservoir which was constructed by the U.S. Bureau of Reclamation in 1940's as a part of the Colorado-Big Thompson Project. It is located west of the City of Fort Collins, CO. It is at an elevation of 5430 feet, and is 6.7 miles long, 0.9 miles wide with an average depth of 80 feet. It has a hydraulic residence time of approximately one year. It stores and provides water for municipal, agricultural, recreational, and industrial uses. Spikes in geosmin levels in Horsetooth Reservoir have been recorded in fall seasons since 2003, and a recent and relatively severe geosmin episode occurred in 2008 with a concentration of 25 ng/L measured at the FCWTF intake. This episode was handled by the FCWTF by increasing the dosage PAC and blending source waters (increasing the intake from Cache La Poudre River). If high geosmin levels continue to occur in Horsetooth Reservoir future Master Planning efforts may need to provide for an upgrade for the FCWTF's PAC feed system. A realistic range of PAC dosages and contact times will be required to facilitate future planning and design. To determine effective dosages and contact times, thirteen combinations of geosmin and PAC concentrations were run over a contact period of 90 minutes (and up to

6 hours for selected combinations). Also the effect of presence of organic matter (reported as total organic carbon, TOC) was investigated as the other source water (Cache La Poudre River) which may be used to dilute the geosmin can have higher TOC levels. The data obtained from the laboratory experiments were analyzed and modeled using a statistical software (Stat Ease Design Expert®, version 8) to confirm the results and to predict the effective PAC dosages and contact times for other geosmin concentrations not tested by this study. A simple equation was developed by the model to be adopted by the drinking water utilities to determine the required PAC dosage and contact time for effective geosmin removal.

This thesis has two main chapters. The first chapter gives the background information obtained through a literature review on algae blooms, problematic algal metabolites, and treatment options to remove such metabolites from source waters for potable and palatable drinking water. The second chapter is prepared in a manuscript format for an academic journal submission. In the second chapter, materials, experimental methods, results, statistical analyses, and conclusions obtained from this research are presented. The raw data is also provided in a tabulated form in the appendices attached at the end.

1.0: LITERATURE REVIEW

Occurrence of Algal Metabolites in Surface Waters and Their Treatment

1. Algae in Surface Waters

1.1. Types of algae

There are many types of blue-green algae (cyanobacteria) that produce off-flavor compounds. The common species of cyanobacteria that produce potent odorous compounds include *Anabaena, Cylindrospermopsis, Oscillatoria, Phormidium,* and *Lyngbya* (Suguira et al., 1997; Ho et al., 2009; Graham et al., 2010). Henatsch and Juttner (1986) noted that the production of geosmin is most commonly associated with the filamentous cyanobacteria in aquatic habitats. Cyanobacteria mats are found in lakes that have higher levels of nutrients (phosphorous and nitrogen) and algae blooms usually occur in late summer and early fall (Watson, 2004). Taste and odor episodes are also caused by several other organisms that cause problems for consumers and water distributors. These include actinomycetes, fungi, and myxobacteria (Young et al., 1995; Watson, 2004; Zuo et al., 2009). As stated by Zuo et al. (2009), actinomycetes have been found in water distribution pipeline deposits and various aquatic systems, adding to the complexity of removing the organic odors.

1.2. Conditions that favor algal blooms

1.2.1. Nutrients

There are several key nutrients which contribute to the growth of cyanobacteria in eutrophic lakes. Sabater et al. (2003) demonstrated that high levels phosphorous, at 0.4 mg/L, coupled with nitrogen limited conditions are ideal for massive growths of blue-green algae. Watson (2004) and Downing et al. (2001) reinforce the findings of Sabater et al. (2003) by showing that moderate levels of total phosphorous contribute to occurrences of cyanobacterial blooms in summer and late fall and reports that phosphorous levels in the range of 30 – 70 ug/L are the most conducive for cyanobacteria growth.

1.2.2. Temperature

A laboratory-scale study conducted by Saadoun et al. (2001) demonstrated that geosmin is produced at high levels at a temperature range of 15 to 30 °C, with maximum production at 20 °C. Other studies, however, have found conflicting results. For example, a study conducted in China by Zhang et al. (2009) showed the optimal temperature for geosmin production was at 10 °C, (with about 75% less growth at 25 and 35 °C); in another study, Saadoun et al. (2001) noted no correlation between water temperature and geosmin at Lake Ogletree in Auburn, AL which had minimum water temperatures of 15 °C. However, it has been known that geosmin blooms usually occur during warm summer and fall months indicating that warmer temperatures may have a positive effect on algae bloom formation (Jöhnk et al., 2008).

1.2.3. TOC

Sabater et al. (2003) and Stal (1995) determined that organic carbon aids cyanobacteria growth through photosynthesis or fermentative metabolism. It has been shown that cyanobacteria utilize the surrounding organic carbon sources; such as glycogen, acetate, ethanol, or lactate, for growth (Stal, 1995). Smith (1983) showed that glycogen is completely oxidized to CO_2 through oxidative pentose phosphate pathway where glycogen is catabolized to oxygen.

1.2.4. Light Intensity/Sunlight

The study conducted by Rashash et al. (1995) showed that low light conditions promote geosmin production. Low-light intensity of 7 uE/m^2/s showed an increase of 10^5 to 10^7 cells/mL over 40 days (Rashash et al., 1995). Zhang et al. (2009) also reported that lower light intensities (10 umol/m^2.s) increase geosmin production by cyanobacteria. On the other side, sunlight that is too intense can inhibit growth and even lead to the degradation of algal cells (Taylor et al., 2006). Cyanobacteria reflect the blue and green wavelengths and absorb energy in the red and blue wavelengths of light for photosynthesis with wavelengths between 400-700 nm which are ideal for photosynthetic growth (Gottler et al., 2007; Taylor et al., 2006).

1.3. Algal metabolites

1.3.1. Taste-and-odor compounds

Two of the most common algal metabolites which cause taste and odor problems in drinking water are geosmin and 2-methylisoborneol (2-MIB). Geosmin and 2-MIB are tertiary alcohols generated as odorous secondary metabolites by cyanobacteria (Ho et al., 2009; Zuo et al., 2009). Cyanobacteria produce geosmin and 2-MIB throughout their life cycle and these metabolites are stored within the cells or released from the algae, especially when they die and decompose (Rashash et al., 1995; Watson, 2004). Geosmin has an odor threshold in the part per trillion range, around 4 to 10 ng/L; Henry's law constant (at 20 °C) of 0.0023; molecular weight of 182.31 g/mol; and water solubility of 150.2 mg/L (at 20 °C) (Bruce et al., 2002; Omur-Ozbek and Dietrich, 2005). Natural degradation of geosmin is fairly slow, around 3 days, and the main path for removal is through microbial degradation (Lawton et al., 2003). Brownlee et al. (2007) showed that geosmin is stable for a year when stored in municipal (chlorinated) tap water at 2-4 °C with no headspace.

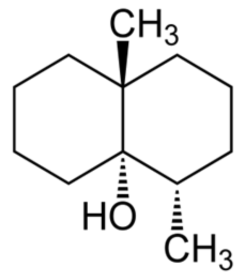

Figure 1.1: Geosmin structure

1.3.2. Toxins

Blue-green algae may also produce various toxins which can be harmful to the human body. The cyanotoxins can be divided into three main groups by their toxicity mechanism: hepatotoxins (that cause liver damage) including cylindrospermopsins and microcystins; neurotoxins (that cause neural system damage) including anatoxins, homoanatoxins, and saxitoxins; and dermatoxins (that cause skin damage) such as lyngbyatoxins and aplysiatoxins (Smith et al., 2008; Graham et al., 2010). All cyanotoxins have varying levels of toxicity which vary by orders of magnitude. For example the World Health Organization set a tolerable daily intake for microcystin at 0.4 ug/kg/d and set a guideline limit of 1 ug/L in drinking water. This is the 'non-cancer endpoint' level where ingesting greater quantities could lead to cancer formation in the body (WHO, 1999). As found by Graham et al. (2010), even though consumers are informed that there are no health risks associated during geosmin episodes, it was shown that cyanotoxins can co-occur with taste-and-odor (T&O) incidents. This highlights the need for concern of potential health hazards during T&O events.

1.3.3. Other organic compounds

Production of trihalomethanes (THMs) and haloacetic acids (HAAs) occur when extracellular organic matter (EOM) and algal matter is chlorinated (Plummer and Edzwald, 2001; Nguyen et al., 2005). In the study conducted by Plummer and Edzwald (2001) chlorinated algal cells (*Cyclotella* sp.) produced THM levels of 58 and 76 ug/L with 1 and 3 mg/L ozone and 7 day reaction period. Wert and Rosario-Ortiz (2011) showed that the formation of THMs and HAAs could be reduced with the addition of ozone since NOM is converted from a hydrophobic to a hydrophilic character. In the study by Fang et al. (2010a), it was found that addition of ammonia lowered the formation of most DBPs. Also levels of nitrogenous disinfection by-products (N-DBPs) showed an increase when nitrogen rich algal cells (*Microcystis aeruginosa)* were chlorinated (Fang et al., 2010a).

1.4. Problems with algal metabolites

1.4.1. Off-flavors in drinking water (Geosmin & 2-MIB)

Geosmin and 2-MIB produce similar but distinctive odors at very low concentrations (parts per trillion). Geosmin can be perceived as an earthy, stagnant, grassy, beetroot, or moldy odor, whereas, 2-MIB is recognized as either a musty, brazil nuts, or peaty smell (Young et al., 1995; Omur-Ozbek and Dietrich, 2005). Taste descriptors for geosmin and 2-MIB are similar to their odor descriptors, respectively. Both compounds are detected at around 4 to 10 ng/L, depending on the sensitivity of the consumer (Bruce et al., 2002).

Even though geosmin and 2-MIB do not pose a health concern, their presence in the tap water worries the consumers and leads to perception of contamination. Off-flavor of tap water also causes loss of trust to the efficiency of the water treatment utilities. For this reason billions of dollars are spent each year to remove the odorants from finished water (McGuire, 1995). To prevent consumer complaints South Korea and Japan has set guideline limits for geosmin and 2-MIB in tap water at 10 ng/L.

1.4.2. Disinfection by-products (DBPs) (organics)

DBPs are formed when organic material that is not removed during water treatment comes in contact with a disinfectant. Trihalomethanes (THMs) and haloacetic acids (HAAs) are common DBPs created in the water treatment process which pose regulatory and health concerns (Bruce et al., 2002). The US EPA (1998) set maximum contaminant levels (MCLs) for total THMs at 0.08 mg/L and HAAs at 0.06 mg/L, based on an annual average. THMs and HAAs are environmental pollutants and many forms are cancerous. The release of algal organic matter (AOM), extracellular or intracellular, produces chloramines and haloacetaldehydes in drinking water systems as the AOM isn't removed by common treatment techniques (Fang et al., 2010b).

1.4.3. Adverse health effects (toxins)

The toxins produced by the cyanobacteria are associated with severe health risks. Toxicosis of alkaloid neurotoxins lead to paralysis and eventually death by respiratory trouble, even in low amounts. Alkaloids are naturally occurring chemical compounds that are produced by bacteria, fungi, and plants. Hepatoxins have been shown to inhibit protein phosphates, loss of cell structure and death, cellular necrosis, atrophy, and tumor promotion and mutation (Smith et al., 2008). As indicated by Smith et al. (2008), hepatotoxins are accumulated in the kidney, intestine, and skeletal muscle of humans whereas dermatoxins cause intestinal bleeding, stomach ulcers, and ultimately death due to hemorrhagic shock if ingested. When the dermatoxins are applied topically, dermatitis, blisters, and necrosis occur (Smith et al., 2008).

2. Treatment of Algal Metabolites

2.1. Activated Carbon

2.1.1. Types of activated carbon

Activated carbon is produced from many different sources, including various plant and coal derived carbons. Plant based activated carbon is made from wood and coconut shells and can be applied in either granular or powdered form (Sugiura et al., 1997; Liang et al., 2005; Ho et al., 2009). Activated carbon may also be coal based, including bituminous or liginite, and is also applied in either granular or powdered form (Sugiura et al., 1997; Bruce et al., 2002). Each brand of powdered activated carbon (PAC) is unique, with different molasses numbers, iodine numbers, material types, and pore size distributions, and selection of PAC depends on water quality characteristics of the raw water.

Activated carbon is created using thermal, chemical, or biological reactivation. Thermal reactivation is the process where carbon materials are pyrolyzed at a minimum temperature of 1100 Kelvin under anoxic conditions. Chemical regeneration of carbon occurs when solvents or oxidizing agents are mixed with organic carbon prior to heating. Biological regeneration is the addition of biological species to aid in the adsorption of contaminants (Alvarez et al., 2004).

2.1.2. Removal of algal odorants by activated carbon

Removal rates of drinking water odorants by activated carbon can vary widely, anywhere from 30% to upwards of 90%, depending on the influent water characteristics, odorant concentrations in source water, and activated carbon dosage. Results for odorant removal and water quality parameters from several studies were summarized in the text below as well as in Table 1.1. A study performed by Jung et al. (2004) found that a powdered activated carbon (PAC) dose of 30 mg/L achieved 70.4 to 87.3% removal of initial concentrations of 106 to 220 ng/L geosmin. It was also reported that the removal efficiency of geosmin increased in proportion to PAC dosage. A recent study performed by Ho et al. (2009) looked at coal and wood based PAC for contact times of 5, 15, and 70 minutes; geosmin concentrations of 70 and 80 ng/L; and PAC dosages of 10 and 30 mg/L, and reported that removal rates ranged from 10 to 90%. Lower removal rates occurred at shorter contact times and lower PAC dosages. For example, 10% removal occurred with a PAC dose of 10 mg/L, initial geosmin concentration of 70-80 ng/L, and a contact time of 5 minutes (Ho et al., 2009). Whereas 90% removal was achieved with a PAC dose of 30 mg/L, initial geosmin concentration of 70-80 ng/L, and contact time of 70 minutes. (Ho et al., 2009). Tests conducted by Bruce et al. (2002) found removal rates of 93% for PAC 20B brand carbon (bituminous coal based), 87% for Hydrodarco-B (lignite coal based), and 90% for WPM (coal based). Tests were conducted with initial geosmin concentrations of 25 to 150 ng/L, 15 mg/L of the particular PAC brand, and contact time of 240 minutes. Further testing conducted by Bruce et al. (2002) found bituminous coal performed better than the lignite or wood based coal. A similar study by Sugiura et al. (1997) found the performance of wood (WAC), coconut (CAC), and coal

(YAC) based activated carbons best removed geosmin in the following order: WAC > CAC > YAC. Ho et al. (2009) suggested that coal based carbons perform better than wood based since they contain a greater volume of micropores for the adsorption of geosmin.

Table 1.1 Geosmin Removal with PAC

Citation	PAC Type	PAC (mg/L)	Geosmin (ng/L)	Removal %	Contact Time (min)	pH	Temp (°C)	Turbidity (NTU)	TOC/DOC (mg/L)
Bruce et al. (2002)	HDB WPM 20B	15	25 – 150	87 90 93	240	8.11 – 8.39	21.1 – 24.9	2.2 – 7.6	2.49 – 2.67 (DOC)
Ho et al. (2009)	PAC-A PAC-P	10 30 10 30	70 - 80	30 – 75 60 – 95 10 - 45 35 – 80	5, 15, 70	7.7 – 7.9	N/A	N/A	8.2 – 11.8 (DOC)
Jung et al. (2004)	N/A	30	106– 220	70.4 – 87.3	62	6.9 – 7.9 (avg 7.3)	N/A	0.8 – 13.1 (avg 2.6)	1.15 – 3.51 (avg 2.02) (TOC)

2.2 Advanced Oxidation

2.2.1. Ozone

Ozone is another treatment method for the removal of cyanobacterial metabolites and can be coupled with chlorine or chlorine dioxide to improve the removal efficiency. It has been shown that hydroxyl ($HO^{\cdot}$) radicals, are strong oxidants and are the primary mechanisms for removal of geosmin (Bruce et al., 2002). Results for odorant removal and water quality parameters from several studies were summarized in the text below as well as in Table 1.2. Bruce et al. (2002) found removal rates at 97% at 12 and 20 minutes, with 81% removal in the first minute for an initial geosmin concentration of 100 ng/L for an ozone dose of 2.5 mg/L. A study conducted by Liang et al. (2007) reported removal rates of 61.1%, 94.9%, and 99.9% at respective pH values of 5, 7, and 9 after 20 minutes for geosmin at 400 ng/L and ozone at 0.35 mg/L. From this experiment Liang et al. (2007) concluded that higher pH values allowed for greater geosmin removal since more $HO^{\cdot}$ radicals are formed. In another experiment, Liang et al. (2007) looked at the effects of background organics and found removal rates were highest in pure water, then raw water, and lastly settled water. The raw water had an alkalinity of 120 mg/L as $CaCO_3$ and TOC of 2.91 mg/L, whereas, the settled water had an alkalinity of 110 mg/L as $CaCO_3$ (obtained by flocculating the raw water with 2.5 mg/L polyaluminum chloride) and TOC of 1.93 mg/L. Experimental results indicated removal rates ranging from 77 to 90% for geosmin levels of 100 ng/L (Liang et al., 2007).

Table 1.2 Geosmin Removal with Ozone

Citation	Ozone (mg/L)	Geosmin (ng/L)	Removal %	Contact Time (min)	pH	Temp (°C)	Turbidity (NTU)	Alk. (mg/L $CaCO_3$)	TOC/DOC (mg/L)
Bruce et al. (2002)	2.5	100	97*	20	8.11 - 8.39	21.1 - 24.9	2.2 - 7.6	N/A	2.49 - 2.67 (DOC)
Liang et al. (2007)	0.35	400	61.08, 94.89, 99.86#	40	5, 7, 9	20	N/A	N/A	N/A
Liang et al. (2007)$	1, 2, 3	100	77 - 90	10	7	20	N/A	110, 120	2.91 & 1.93 (TOC)

* Removal at 81% within the first minute

\# Removal after 20 minutes

$ Investigating effects of organic matter

2.2.2. UV/Hydrogen peroxide

Oxidation with UV and hydrogen peroxide are less common treatments for geosmin but are still quite effective at removing the odorant. Geosmin removal using UV is best at wavelengths less than 254 nm. At around 250 nm wavelength, the photochemical reaction between the electromagnetic field connected to the molecule and that connected with the radiation is strong enough to be effective. It was reported that the removal of geosmin was enhanced with the addition of hydrogen peroxide, as advanced oxidation occurs with the formation of $HO^{\cdot}$ radicals (Rosenfeldt et al. 2005). In a study conducted by Peter and Von Gunten (2007) the second order reaction rate for geosmin using UV/H_2O_2 was determined to be 0.1 (mol/L)/sec. The study also found removal rates of 50-70% for geosmin and 2-MIB from Lake Zurich and Greifensee in Switzerland.

2.3. Nanoparticles (titanium dioxide)

Titanium dioxide has shown great promise for geosmin removal from tap water but isn't yet as popular as other previously discussed treatment options. Lawton et al. (2003) found that titanium dioxide (TiO_2) photocatalyst achieved over 99% removal of geosmin in 60 minutes. The samples were tested in 20-mL thin walled glass vials, with a 1% TiO_2 catalyst solution, irritated by a 280 watt xenon lamp in air for 0, 5, 10, 15, 30 minutes, with Milli-Q water. As expected in photocatalytic processes, removal rates increased with increasing concentrations of catalyst (Lawton et al., 2003). The study by Li et al. (2010) showed a decrease in geosmin from 600 ng/L to 6 ng/L with the use of a Ti/RuO_2-Pt anode with NaCl. The study used a current density of 40 mA/cm^2, 3 g/L NaCl, and contact time of 60 minutes. Additionally, removal reached upwards of 99% when initial concentrations where varied between 60-1200 ng/L, current density of 40 mA/cm^2, 3 g/L NaCl, and contact time of 60 minutes (Li et al., 2010).

3. Water Quality Parameters in Surface Waters

3.1. Organic materials

Organic materials are present in surface waters as they are either introduced by the runoff from the surrounding land or through the biological activities within. The presence of organic materials in the source and drinking waters can be problematic to consumers and water treatment plants. Organic materials impart off-flavors and color to the water. If they are not removed properly from drinking water during the treatment processes, carcinogenic disinfection by-products can be formed when disinfectants are added. Typical levels of total organic material in several Colorado lakes and reservoirs range from 5.4 to 31.9 mg/L (in Gaynor lake which is used for farm irrigation) (Pennak, 1949). Additionally Morris and Lewis (1992) reported that levels of DOC in Lake Dillon, CO vary between 1.43 and 2.37 μg/L. In Horsetooth Reservoir from summer 2002 to fall 2009 TOC levels varied between 2.75 – 3.50 mg/L (Billica and Oropeza, 2010).

3.2. pH

Typical pH levels of surface waters fluctuate between 6.5 and 8.5. Levels vary due to changes in carbon dioxide concentrations, which are influenced by photosynthetic activity (Pennak, 1949). Higher levels of nutrients (nitrogen and phosphorus) and warmer temperatures lead to phytoplankton and aquatic plants that lead to increased photosynthetic activity. Run-off from agriculture is the primary source of nutrients that influence photosynthetic activity (and resulting pH levels). In Colorado, Pennak (1949) found levels of pH ranging from 7.1 to 8.9 at the surface and 6.8 to 8.9 at the bottom of the seven Colorado lakes and reservoirs. The seven lakes and reservoirs studied were: Kossler Lake, Boulder Lake, Allens Lake, Gaynor Lake, Baseline Reservoir, Hayden's

Lake, and Beasley Reservoir (Pennak, 1949). pH levels in the Hansen Feeder Canal, which is the primary influent for Horsetooth Reservoir, fluctuated between 7.25 – 7.75 from winter 2005 to winter 2010 (Billica and Oropeza, 2010).

3.3. Temperature

Temperature can play a vital role in whether cyanobacteria blooms will occur in surface waters. Warmer water temperatures (in an optimal range of 12 to 24 °C) facilitate the growth of cyanobacteria that can result in geosmin outbreaks (Konopka and Brock, 1978). Additionally, cyanobacteria growth increases 1.8 to 2.9 fold over the range of temperatures of 10 to 20°C, and in general growth occurs in temperatures about 18°C (Taylor et al., 2006). Furthermore, it was stated that most cyanobacterial growth occurs in the epilimnion and metalimnion of lakes and reservoirs (Taylor et al., 2006). Water temperatures in several Colorado lakes tested by Pennak (1949) had maximum and minimum surface temperatures of 25.0 and 4.0 °C, respectively, and bottom maximum and minimum temperatures of 19.5 and 4.0 °C. The study by Billica et al. (2010) and Billica and Oropeza (2010) found temperatures at Solider Canyon Dam in Horsetooth Reservoir fluctuated between 5 to 22°C at depths ranging from 50 to 0 meters, respectively when sampled throughout 2009.

3.4. Alkalinity

In the report by Billica and Oropeza (2010) alkalinity levels in Horsetooth Reservoir fluctuated within a narrow range between 25 – 35 mg/L as $CaCO_3$ from summer 2005 to fall 2009. Alkalinity levels drop in the spring and summer since water is brought in by the low-alkaline waters of the Hansen Feeder Canal (Billica and Oropeza, 2010).

3.5. Chlorophyll-a

In the study conducted by Gelder et al. (2003) whole-lake mean annual values and mean summer values in Aurora Reservoir of chlorophyll-a were determined to be 1.75 ug/L and 1.2 ug/L, respectively. The authors highlighted that these levels are indicative of an oligotrophic lake. Newcombe et al. (2002) summarized that some studies showed a direct relationship between the chlorophyll-a and 2-MIB/geosmin levels in reservoirs, whereas several others showed no correlation between chlorophyll-a and geosmin. Horsetooth Reservoir experienced chlorophyll-a levels between 1 to 7 ug/L at 1-meter depth from summer 2005 to fall 2009 (Billica and Oropeza, 2010).

3.6. Nutrients

Nitrogen and phosphorous are key nutrients for the growth of cyanobacteria. Phosphorous has no known severe side effects if consumed; however, certain inorganic nitrogen species can have severe health effects by reducing the amount of oxygen that red blood cells can carry. Phosphorous levels range from 0.01 to 0.1 mg/L, with 0.1 mg/L being the recommended maximum level for rivers and streams. Nitrogen is found in two forms: nitrate and nitrite. The standards for maximum levels of nitrogen in drinking water are 10 mg/L and 0.1 mg/L for nitrate and nitrite, respectively. Levels of nitrate found by Morris and Lewis (1992) in Lake Dillon, CO ranged from <1 to 207 μg/L and levels of particulate phosphorous ranged from 1.6 to 10.0 μg/L. Sabater et al. (2003) demonstrated that high levels phosphorous, at 0.4 mg/L, coupled with nitrogen limited conditions are ideal for massive growths of blue-green algae. The study conducted by Gelder et al. (2003) found levels of total phosphorous at 22 ug/L in Aurora Reservoir. Total phosphorous levels ranged from 0.01 to 0.10 mg/L from summer 2005 to fall 2009 in Horsetooth Reservoir (Billica and Oropeza, 2010). Total nitrogen varied between 0.1 to 0.7 mg/L from summer 2005 to fall 2009 (Billica and Oropeza, 2010).

4. Effects of Water Quality Parameters and Other Factors on Removal of Taste-and-Odor Compounds by PAC

4.1. Organic materials

Presence of organic matter in raw water negatively affects the ability of activated carbon to remove geosmin. It has been shown that natural organic matter (NOM) and dissolved organic carbon (DOC) competes for adsorption sites on the activated carbon (Bruce et al., 2002). Newcombe et al. (1997) indicated that the effect of NOM adsorption largely depends on the charge, size, polarity of the adsorbate, as well as the affiliation between the adsorbate configuration and the activated carbon surface. Srinivasan and Sorial (2011) indicated that a reduction in PAC adsorption occurs when NOM ranges from 3 to 10 mg/L. Removal of 2-MIB can be decreased by as much as 99% depending on the molecular weight of the NOM and pore size of the activated carbon (Newcombe et al., 2002). However, several studies have shown that both DOC and NOM have minimal effect on the adsorption of geosmin onto activated carbon (Sugiura et al., 1997; Ho et al., 2009).

4.2. pH

Sugiura et al. (1997) found that there was a little effect of pH on the adsorption of geosmin onto activated carbon in the range of 4.0 to 9.0. Graham et al. (2000) found slightly better removal of geosmin at pH of 8.0 compared to pH of 5.6 and 5.9, but noted that an error in the data could account for most of the difference.

4.3. Contact time

Several studies have shown that longer contact times between the activated carbon and geosmin increase removal rates (Jung et al., 2004; Ho et al., 2009). For example, Ho et al. (2009) demonstrated that geosmin removal increased approximately 20% when contact time was increased from 15 to 70 minutes. Similarly, Liang et al. (2005) found removal of 2-MIB increased from 50% to 60% when contact time was increased from 50 to 250 minutes with a PAC dose of 20 mg/L and initial 2-MIB concentration of 100 ng/L.

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2.0: MEASURING AND MODELING GEOSMIN REMOVAL FROM A NORTHERN COLORADO RESERVOIR BY POWDERED ACTIVATED CARBON

1. Abstract

Presence of geosmin, an odorous algal metabolite produced by cyanobacteria and actinomycetes, has been an issue in drinking waters in Northern Colorado. Geosmin does not pose a health threat; however, it imparts an earthy taste and odor to the finished drinking water even at very low concentrations (4 -10 ng/L), resulting in consumer complaints and dissatisfaction. Geosmin cannot be removed by conventional water treatment processes, so further treatment is required to achieve concentrations below detection limits. This study investigated the geosmin removal from the raw water obtained from the Horsetooth Reservoir, in Fort Collins, CO by powdered activated carbon (PAC). Raw water samples were spiked with stock geosmin solution to obtain concentrations from 10 to 50 ng/L and stock PAC solution to obtain concentrations from 5 to 20 mg/L. Thirteen different geosmin/PAC concentrations were tested for 90 minutes contact time (and up to 6 hours for selected combinations) and the geosmin removal was determined by headspace solid phase microextraction and gas chromatography/mass spectrometry. Results indicated that 50 to 70% removal was achieved for lower doses of geosmin/PAC combinations, and 80 to 97% removal was achieved for higher PAC dose combinations. Most (65%) of the geosmin removal was achieved within the first thirty minutes. For 54% of the samples, geosmin concentrations in the treated water were

lowered below 4 ng/L after 90 minutes, which is a low enough concentration to prevent consumer complaints. Furthermore, 38% of the samples lowered geosmin concentrations below 4 ng/L after 45 minutes. Additionally three PAC/geosmin combinations that contained 8 mg/L of total organic carbon were examined and a decrease in geosmin removal by 8-12% after 90 minutes was observed. Further analysis with Stat-Ease® Design Expert® (v.8) was used to model geosmin removal to predict required PAC dosages for geosmin levels not tested in this study. The model developed by the Design Expert® considered the initial geosmin concentration, PAC dosing and contact time, and a simple equation was obtained to predict the remaining geosmin concentrations in the treated water. Results from the model fit the data obtained from laboratory measurements and reliably predicted geosmin removal for concentrations not tested.

Keywords: Geosmin, powdered activated carbon, taste and odor, drinking water treatment, SPME, GC/MS, Design Expert®

2. Introduction

Occurrence of algal blooms and off-flavor compounds has been an issue for the drinking water utilities in Northern Colorado that get their source water from lakes and reservoirs. Geosmin is produced as an odorous secondary metabolite by cyanobacteria (Ho et al., 2009; Zuo et al., 2009) (Fig. 2.1) and stored intra-cellularly or released throughout their life cycle. Higher geosmin release occurs when algae die and decompose (Rashash et al., 1995; Watson, 2004). Geosmin is a tertiary alcohol, has a low Henry's law constant (0.0023 at 20 °C), low water solubility (150.2 mg/L at 20 °C), and is a semivolatile aromatic compound (Omur-Ozbek and Dietrich, 2005). Geosmin imparts an earthy taste and odor to the drinking water at very low concentrations (4-10 ng/L). Though not harmful to the consumer, geosmin incidents result in customer complaints (McGuire, 1995) due to off-flavors, especially in the late summer and early fall when geosmin levels typically peak (Watson, 2004; Omur-Ozbek and Dietrich, 2005). Because general population can detect geosmin at 4 to 10 ng/L, even the most minute release of geosmin impacts drinking water utilities (Bruce et al., 2002; Omur-Ozbek and Dietrich, 2005).

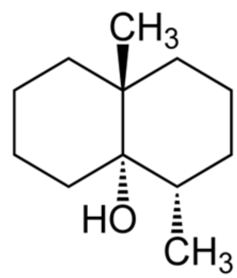

Figure 2.1: Geosmin Structure

Some of the common genera of cyanobacteria that produce geosmin include *Anabaena, Oscillatoria, Phormidium,* and *Lyngbya* (Suguira et al., 1997; Ho et al., 2009; Graham et al., 2010).

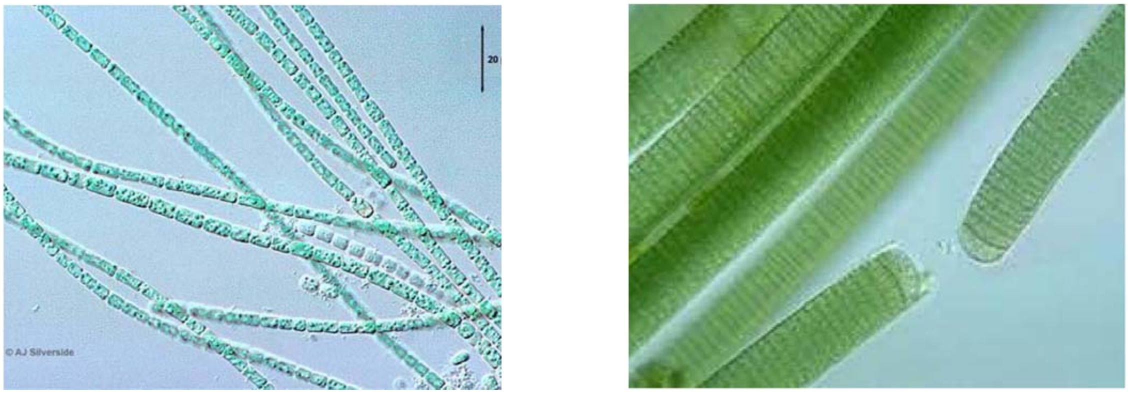

Figure 2.2: Cyanobacteria: *Anabaena (left)* (Hirose and Yamagishi (ed.), 1977) and *Oscillatoria (right)* (Silverside, 2010)

Algae blooms are reported to be positively correlated with nutrients, temperature and light intensity. Cyanobacteria mats are found in lakes that have higher levels of nutrients and blooms usually occur in warm late summer and early fall months (Sabater et al., 2003; Watson, 2004; Jöhnk et al., 2008). Phosphorous concentrations in the range of 30 to 70 ug/L are the most favorable levels for algae growth (Downing et al., 2001). Stal (1995) showed that cyanobacteria use their surrounding organic carbon sources; such as glycogen, acetate, ethanol, or lactate, for growth and hence presence of organic matter may enhance the algae blooms. Cyanobacteria are also known to dominate the surface waters under nitrogen limited conditions as they can fix nitrogen from the atmosphere (Smith, 1983; Wang et al., 2005). A laboratory-scale study conducted by Saadoun et al. (2001) demonstrated that geosmin is produced at high levels at a temperature range of 15 to 30 °C, with maximum production at 20 °C. Other studies, however, have found conflicting results. For example, a study conducted in China by Zhang et al. (2009) showed that the optimal temperature for geosmin production was at 10 °C, (while a higher algae growth was observed at 25 °C). Zhang et al. (2009) also reported that lower light intensities (10 umol/m^2.s) promote geosmin production by cyanobacteria.

Cyanobacteria reflect the blue and green wavelengths and absorb energy in the red and blue wavelengths of light for photosynthesis (Gottler et al., 2007).

Horsetooth Reservoir is a terminal reservoir which was constructed by the U.S. Bureau of Reclamation in 1940's as a part of the Colorado-Big Thompson Project. It is located west of the City of Fort Collins, CO. It is at an elevation of 5430 feet, and is 6.7 miles long, 0.9 miles wide with an average depth of 80 feet. It has a hydraulic residence time of 1approximately one year. It stores and provides water for municipal, agricultural, recreational, and industrial uses including water for the City of Fort Collins Water Treatment Facility (FCWTF). Spikes in geosmin levels in Horsetooth Reservoir have been recorded in fall seasons since 2003. A recent and relatively severe geosmin episode occurred in 2008 with a peak geosmin concentration of 25 ng/L measured in raw Horsetooth Reservoir water at the FCWTF, and a peak geosmin concentration of 53 ng/L within the water column (Billica et al., 2010).

Geosmin is persistent in surface waters and natural attenuation of geosmin is fairly rapid, around 3 days, and the main pathway for removal is through microbial degradation (Lawton et al., 2003). There are several different microorganisms that can biodegrade geosmin including: *Bacillus cereus, Bacillus subtilis, Arthrobacter atrocyaneus, Arthrobacter globiformis, and Rhodococcus moris,* but no definitive pathways for degradation have been found (Ho et al. 2007). Brownlee et al. (2007) showed that geosmin is stable for a year when stored in municipal (chlorinated) tap water at 2-4 °C with no headspace, indicating stability of geosmin even at the presence of an oxidant in the water. Handling geosmin incidents poses a challenge for the drinking water utilities because conventional treatment units are ineffective at removing geosmin from the source water. Hence, more advanced removal methods that employ activated carbon, ozone, nanoparticles, or UV/Hydrogen peroxide are of interest to water utilities. Ozone is an effective method for the removal of cyanobacterial metabolites (61 to 97% removal) and can be coupled with chlorine or chlorine dioxide to improve the removal efficiency. It has been shown that $HO^{\cdot}$ radicals formed, which are strong oxidants, are the primary mechanisms for breakdown and removal of geosmin (Bruce et al., 2002). Nanoparticles (e.g., titanium dioxide), and UV/Hydrogen peroxide are less common and costly treatments but have been shown to achieve very good success in removing geosmin (Lawton et al., 2003; Rosenfeldt et al., 2005).

Powdered activated carbon (PAC) is the most commonly used method for the removal of geosmin because it is inexpensive relative to other methods; existing facilities can be equipped to treat water with PAC easily; and it can be put in use when necessary (during taste-and-odor (T&O) episodes). However, geosmin removal by PAC can vary widely, anywhere from 30% upwards of 90%, depending on the influent water characteristics, geosmin levels, activated carbon dosage, and contact time. Specifically, natural organic matter (NOM) and dissolved organic carbon (DOC) compete for adsorption sites on the carbon and decrease geosmin removal rates (Newcombe et al., 1997; Bruce et al., 2002). The wide range of removal rates reported in previous literature results from the fact that prior researchers have looked at the effectiveness of PAC during particular T&O incidents with different source water characteristics and contact times. Several studies have shown that longer contact times between the activated carbon and geosmin increase removal rates (Jung et al., 2004; Ho et al., 2009). For example, Ho et al. (2009) demonstrated that geosmin removal increased approximately 20% when contact time was increased from 15 to 70 minutes. Similarly, Liang et al. (2005) found removal of 2-MIB increased from 50% to 60% when contact time was increased from 50 to 250 minutes with a PAC dose of 20 mg/L and initial 2-MIB concentration of 100 ng/L.

In contrast, the aim of this research was to conduct a systematic investigation of the effectiveness of PAC at removing geosmin to below-detection limits. This was achieved by determining geosmin removal rates for varying combinations of geosmin and PAC concentrations; as well as investigating the effect of contact time and presence of organic carbon (reported as total organic carbon, TOC) on geosmin removal.

3. Materials and Methods

3.1. Materials and Instruments

Geosmin and TCA (2,4,6-trichloroanisole) standards and GC grade methanol were obtained from Sigma Aldrich (Pittsburgh, PA). One gallon amber glass jars with Teflon coated screw caps, 1 liter amber glass bottles with Teflon coated screw caps, and 40 mL amber glass EPA approved volatile organics analysis (VOA) vials were purchased from Fisher Scientific (Pittsburgh, PA). Powdered activated carbon (Hydrodarco-B) was supplied by Norit Americas Inc. (Marshall, TX). A 50-mL glass syringe with glass plunger, graduated every 2-mL, was purchased from Sigma Aldrich (Pittsburgh, PA). Whatman glass fiber filters (44 um pore size) and Teflon coated stir bars were purchased from Fisher Scientific (Pittsburgh, PA). High purity sterile sodium chloride was acquired from Fisher Scientific (Pittsburgh, PA). A 5.5 liter isotemperature Thermo Scientific Precision water bath, model number 2831, with ±0.2 °C uniformity and ±0.1 °C control resolution was purchased from Fisher Scientific (Pittsburgh, PA). Solid-phase microextraction (SPME) fibers coated with Polydimethylsiloxane/Divinylbenzene (PDMS/DVB) at 65 μm thickness, the SPME holder and the SPME GC-inlet liner were purchased from Sigma-Aldrich (Pittsburgh, PA). Agilent 5890 gas chromatograph (GC) equipped with an Agilent DB-5 MS (30 m, 0.25 mm i.d., 0.25 um) column connected to an Agilent 5973 mass spectrometer (MS) were used for sample analyses (Santa Clara, CA). Water quality parameters: pH (Model 5190 Platinum Series pH Electrode), conductivity (4-pole Conductivity Probe), and dissolved oxygen (DO) (DO probe) were measured using a Hach sensION156 Portable Mutliparameter Meter (Loveland, CO). Turbidity was measured with a Hach 2100N Turbidimeter (Loveland, CO). Temperature was measured with an H-B Dual Scale Thermometer (-10 to 260 °C) (Collegeville, PA). TOC was measured by the City of Fort Collins Water Quality Laboratory using a Sievers 5310c Laboratory TOC Analyzer.

3.2. Methods

Thirteen combinations of geosmin and PAC at various concentrations (Table 2.1) were tested in triplicates over 8 months to determine the effectiveness of PAC at removing geosmin across various PAC dosages (5 to 30 mg/L), initial geosmin concentrations (10 to 50 ng/L), and contact times (15 to 90 min) for an average (~3.76 mg/L) TOC concentration. The geosmin concentrations tested were selected to reflect the levels that could potentially occur at the Horsetooth Reservoir. The PAC concentrations tested were selected based on the findings reported by the previous studies and conservative levels to treat geosmin concentrations of interest. The TOC level indicates the average conditions in Horsetooth Reservoir. Stat Ease® Design Expert® (version 8) was employed to select the geosmin and PAC combinations for this study.

Design Expert® uses multilevel factorial screening designs to find critical influences that can lead to revolutionary improvements in experimental and industrial designs. It allows for general factorial, two-level factorial, fractional factorial, Plackeet-Burman designs, and numerical optimization. Two-level factorial designs identify the vital factors which affect a process or product in order to make ground-breaking improvements. Response surface models find the optimal process settings to achieve peak performance. Mixture design techniques discover the ideal formula for product design. Applications vary widely and any process that involves mixing components can see improvements using design expert. For this study, a two factorial design approach was used to determine the optimum PAC and geosmin concentration combinations for effective removal rates. Unrealistic combinations (e.g., 10 ng/L geosmin and 20 mg/L PAC) suggested by the software were eliminated from the identified PAC/geosmin combination list. To determine the effects of higher TOC level (8 mg/L) on removal efficiency, three combinations of PAC and geosmin were conducted at 10, 15, 20 mg/L PAC dosages for 20 ng/L initial geosmin concentration. To investigate the effects of longer contact times, five selected combinations; PAC 5 mg/L and geosmin 10 ng/L, PAC 10 mg/L and 20 ng/L geosmin, PAC 12.5 mg/L and geosmin 30 ng/L, PAC 15 mg/L and geosmin 40 ng/L, and PAC 20 mg/L and geosmin 50 ng/L; were run for a maximum contact time of 6 hours.

Table 2.1: PAC/Geosmin Combinations for Average TOC Experiments

Run #	PAC Concentration (mg/L)	Geosmin Concentration (ng/L)
1	5	10
2	5	15
3	10	15
4	10	20
5	10	30
6	15	20
7	15	30
8	15	40
9	20	30
10	20	40
11	20	50
12	30	40
13	30	50

The experimental water samples (from Horsetooth Reservoir (for average TOC experiments) and Cache la Poudre River (for high TOC experiments)) were collected at the inlet to the Fort Collins Water Treatment Facility (FCWTF) in gallon amber glass jugs and were stored at 4 ^{o}C in the dark. Stock solutions of geosmin and TCA (internal standard) were prepared in methanol in VOA vials, both at 0.04 mg/L concentration and were stored at 4 ^{o}C in the dark. PAC stock solution was prepared in deionized water obtained from the Barnstead NANOpure Diamond nanofilter at 10 g/L concentration.

For each geosmin and PAC combination, triplicate runs were tested as explained below. For each run, three 1 liter amber glass bottles with screw cap lids were filled with the experimental water.

Figure 2.3: Expermintal set-up

The selected water quality parameters (temperature, DO, pH, turbidity, and conductivity) were measured at the beginning of each run. The TOC data were measured by the Fort Collins Water Quality Laboratory. The experimental water was obtained from Horsetooth Reservoir for the average TOC runs and longer contact time experiments. Cache la Poudre River water was diluted with Horsetooth water to obtain the 8 mg/L TOC level for the higher TOC runs. A Teflon coated stir bar was placed in each bottle and the experimental water was mixed without creating a vortex (Watson et al., 2000). The first bottle served as the control (to account for any loss of geosmin during testing) and was only spiked with the stock geosmin solution to obtain the desired concentration (e.g., 1 mL from the 0.04 mg/L stock solution to obtain 40 ng/L). The other two bottles were spiked with the same amount of geosmin as the control and with PAC stock solution to obtain the corresponding combination concentration (e.g., 1.5 mL of 10 g/L of PAC stock solution to obtain 15 mg/L PAC in the bottle). The first samples (20 mL, in duplicates) were collected at 0 minute from all bottles right after the addition of the geosmin and/or PAC. Then the bottles were capped until next sample collection time at 15, 30, 45, 60, and 90 minutes. For the extended runs more samples were collected at 120, 180, and 360 minutes. The collected samples were immediately filtered through glass fiber filters and were placed in 40-mL amber glass VOA vials that contained 5 g of sodium chloride. 20 uL of TCA stock solution was added to each vial to obtain a concentration of 10 ng/L to serve as an internal standard. The vials were then capped with open top screw caps lined with Teflon septa and stored at 4 ^{o}C in dark until all of the samples were collected for each run.

For the analysis of geosmin remaining in the samples a standard curve was obtained for every run by preparing geosmin solutions in deionized water at 1, 5, 10, and 25 ng/L concentrations in the VOA vials. The standard curve vials also received 5 g of sodium chloride. The vials were placed in a water bath at 75 ± 2 °C and heated for 10 minutes. The geosmin in the headspace was extracted with the SPME fiber for 20 minutes and the geosmin was desorbed at the inlet (equipped with the SPME GS inlet liner) of the GC for 2.5 minutes, which was set to 250 °C, pressure of 100 kPa (at 124 °C) and operated in splitless mode. The GC oven was programmed for a run time of 4.5 minutes, with an initial temperature of 124 °C increasing to 178 °C at 12 °C per minute. The helium carrier gas was operated at 1.6 mL/min with a pressure of 145 kPa. Geosmin and TCA were eluted from the GC column connected to the MS. The MS was set to selected ion monitoring mode for TCA (m/z 195) until 3.75 minutes and then to geosmin (m/z 112, 125, 182) until the run was complete. TCA eluted at around 3.43 min and geosmin eluted at around 4.16 min. The geosmin concentrations in the samples were calculated using the standard curve. The detection limit for geosmin with the headspace SPME-GC/MS analysis was given as 0.3 ng/L by the previous researchers (Lloyd et al., 1998, Watson et al., 2000; Omur-Ozbek et al., 2005).

Figure 2.4: Extraction with SPME

Figure 2.5: Analysis by GC/MS

Design Expert® was also used to model the geosmin removal by PAC and to predict the remaining geosmin concentrations for different PAC/geosmin/contact time combinations not tested by this study. For the model, a multifactor Response Surface Model (RSM) was utilized. Three important parameters (initial geosmin concentration, PAC dose, and contact time) were considered for the model. The 65 data points obtained from the laboratory measurements for the thirteen combinations at five contact times (15, 30, 45, 60, and 90 min) were entered into the software. Linear, 2FI (2-factor interaction), and quadratic models were analyzed and the 2FI was selected as the best model to predict the remaining geosmin concentrations. The 2FI model had the best fit for the actual versus predicted data as it contained additional interaction terms in the equation obtained for prediction. To verify the model developed and the prediction of the remaining geosmin concentrations, the combination of PAC 12.5 mg/L and geosmin 30 ng/L was also run for a 90 minute contact time and the results were checked against the geosmin concentrations predicted by the model.

4. Results and Discussion

4.1. Results

Water quality parameters measured for all the average TOC runs (including the longer contact time experiments) are summarized in Table 2.2. The water quality in Horsetooth Reservoir water changed slightly over time and the minimum, maximum, and average values are presented as well as the standard deviation for each parameter.

Table 2.2: Water Quality Parameters for the Average TOC Runs

Parameter	Minimum	Maximum	Average	Standard Deviation
Temp (°C)	15	18	15.8	0.81
pH	7.2	7.9	7.6	0.15
DO (mg/L)	8.1	9.8	9.2	0.40
Turbidity (NTU)	1.85	4.45	2.52	0.56
Conductivity (mg/L)	73	107	76.9	5.67
TOC (mg/L)	3.37	3.90	3.76	0.16

The removal efficiency of geosmin by PAC from Horsetooth Reservoir water was determined for thirteen different geosmin/PAC concentration combinations at 15, 30, 45, 60, and 90 minute contact times for the average TOC levels (~3.76 mg/L). The results indicated that lower initial geosmin concentrations and larger PAC dosages resulted in greater removal rates. Seven of the thirteen combinations tested decreased geosmin concentrations below 4 ng/L (with an eighth combination just over the limit at 4.4 ng/L) after a 90 minute contact time, which is the FCWTF finished water treatment goal to prevent consumer complaints. Removal rates varied from 32.3 to 97.6% across all PAC/geosmin combinations and contact times. Table 2.3 shows the percent removal and remaining geosmin concentrations for the PAC/geosmin combinations after 15, 30, 45, 60, and 90 minutes contact times. The lowest removal percentage of 32.3% was observed with the lowest PAC/geosmin combination of 5 mg/L PAC and 10 ng/L geosmin after 15 minutes, and the greatest removal percentage of 97.6% was achieved with the combination of 30 mg/L PAC and 40 ng/L geosmin after 90 minutes. Only the combinations that contained 5 mg/L PAC removed less than 60% of geosmin while the rest of the PAC dosages removed at least 70% of geosmin after 90 minutes. The odor threshold for geosmin is around 4 to 10 ng/L (Kim et al., 1997; Bruce et al., 2002) and the FCWTF has established 4 ng/L as the acceptable geosmin concentration in the finished water. As seen in Table 2.3, all combinations removed geosmin to at least down to less than the upper threshold concentration (of 10 ng/L), with the maximum remaining geosmin concentration of 8 ng/L occurring at the 10 mg/L PAC and 30 ng/L geosmin combination after 90 minutes. Over half of the combinations met the FCWTF's standard of 4 ng/L after 90 minute contact time. The majority of the combinations that were below the FCWTF's standard were in the range of 0.9 to 3.8 ng/L (See Appendix A for the graphs of the results).

Table 2.3: Results for All PAC/Geosmin Combinations

PAC Conc. (mg/L)	GSM Conc. (ng/L)	Percent Removed					Concentration Remaining (ng/L)				
		15 min	30 min	45 min	60 min	90 min	15 min	30 min	45 min	60 min	90 min
5	10	32.3±10.4	40.0±5.6	45.6±4.3	49.0±5.8	54.4±3.5	6.5±0.6	5.7±0.4	5.2±0.4	4.9±0.3	4.4±0.1
5	15	36.6±0.9	41.9±1.1	48.4±1.4	56.6±1.7	59.9±0.5	9.5±0.1	8.7±0.2	7.7±0.2	6.5±0.3	6.0±0.1
10	15	45.5±1.0	68.4±1.3	75.0±0.9	78.0±0.9	80.4±0.3	8.2±0.2	4.7±0.2	3.8±0.1	3.3±0.1	2.9±0.0
10	20	44.4±1.7	49.8±1.9	57.7±1.7	62.0±2.7	69.3±5.0	10.4±0.9	9.4±0.8	7.9±0.5	7.1±0.6	5.8±1.1
10	30	33.1±1.0	55.4±7.0	63.7±2.8	66.8±2.6	73.7±4.2	20.3±0.8	13.6±2.7	11.0±1.4	10.1±1.3	8.0±1.7
15	20	51.0±0.4	59.5±0.4	70.7±0.7	76.3±1.1	80.9±1.3	9.8±0.1	8.1±0.1	5.9±0.1	4.7±0.2	3.8±0.3
15	30	50.7±3.6	65.0±5.7	75.6±3.6	83.0±1.4	87.5±0.4	14.8±1.1	10.5±1.7	7.3±1.1	5.1±0.4	3.8±0.2
15	40	51.5±1.4	65.4±2.7	73.5±1.9	76.5±1.3	81.5±1.8	19.2±0.6	13.7±0.9	10.5±0.6	9.3±0.5	7.4±0.7
20	30	62.7±2.6	74.2±3.7	85.1±6.8	92.5±1.2	94.3±0.3	11.2±0.8	7.8±1.1	4.5±2.0	2.3±0.4	1.7±0.1
20	40	60.2±8.5	72.5±4.6	82.3±2.6	86.7±1.3	92.0±0.6	15.9±3.4	11.0±1.8	7.1±1.0	5.3±0.5	3.2±0.2
20	50	67.8±1.2	76.8±1.1	82.6±2.0	86.1±0.8	88.0±0.7	15.7±0.9	11.3±0.4	8.4±1.0	6.7±0.5	5.9±0.2
30	40	75.2±1.2	90.4±1.0	93.4±0.4	94.6±0.4	97.6±0.3	9.9±0.5	3.9±0.4	2.6±0.2	2.1±0.1	0.9±0.1
30	50	81.0±2.7	87.4±1.4	91.0±0.3	93.1±0.6	94.8±0.4	9.5±1.3	6.3±0.7	4.5±0.1	3.4±0.3	2.6±0.2

* ± Shows standard deviation for triplicate runs

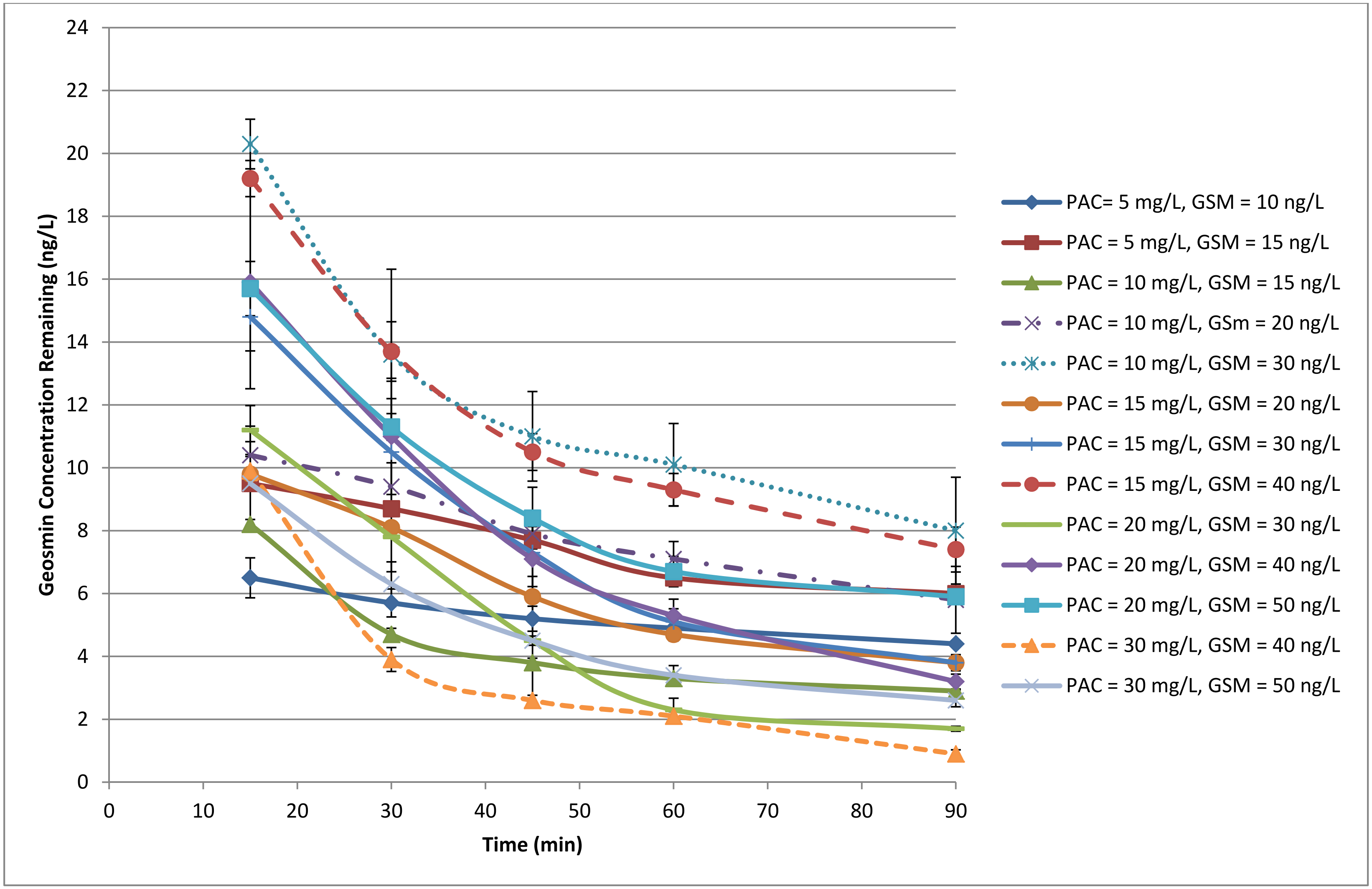

Figure 2.6: Results for All PAC/Geosmin Combinations

* Bars show standard deviation for triplicate runs

Additional five runs (to the thirteen abovementioned runs) for PAC/geosmin combinations revealed that increasing the contact time to six hours only increased removal rate by about 6.6 to 25.7 % beyond 60 minutes. Table 2.4 shows the combinations and the increase in geosmin removal rates. The combinations of PAC 20 mg/L and geosmin 50 ng/L achieved the lowest increase in percent removal, and PAC 10 mg/L and geosmin 20 ng/L achieved the greatest increase in percent removal after the first 60 minutes. Hence only 2.26 to 7.84 ng/L of geosmin was removed beyond the 60 minutes contact time.

Table 2.4: Increase in Geosmin Removal Rate for up to 6-Hour Contact Time

PAC Conc. (mg/L)	GSM Conc. (ng/L)	Increase in Percent Removed			
		1 to 2 hr	2 to 3 hr	3 to 6 hr	Total (from 1-6 hours)
5	10	6.0	10.4	6.2	22.6
10	20	9.7	8.3	7.7	25.7
12.5	30	5.3	8.8	2.0	16.1
15	40	8.6	8.3	2.7	19.6
20	50	4.1	0.8	1.7	6.6

The data obtained from the 13 runs (shown in Table 2.1) were used to create a model in Stat-Ease® Design Expert® (version 8) software to predict remaining geosmin concentrations. The model predicted all the tested values within -3.1 to +5.6 ng/L of the measured geosmin concentrations, mostly predicting a higher value for the geosmin remaining. The results showed that Design Expert® underestimates the amount of geosmin removed. This will give confidence to the water utilities in predicting their geosmin removal and will account for any error in PAC dosing, initial geosmin concentration, or contact time (See Appendix B for the comparison of all the values measured in the laboratory and predicted by the model). A regression analysis by the

Design Expert® (R^2=0.77) showed that there was no significant difference between the measured and the predicted values (Fig. 2.2(a)).

An extra combination of PAC at 12.5 mg/L and geosmin at 30 ng/L was also experimentally tested and intentionally omitted from the Design Expert® model. This combination was used to verify the accuracy of the model. Table 2.5 shows the comparison between the measured and predicted values for this combination. The results show a very good prediction by Design Expert® with remaining geosmin concentration varying between -1.6 to +1.1 ng/L and the standard deviation varying by 0.34 - 1.15.

Table 2.5: Comparison of PAC 12.5 mg/L and Geosmin 30 ng/L

Time (min)	Measured (ng/L)	Predicted (ng/L)	Std. Dev.	Difference (ng/L)
15	14.5	13.4	0.80	1.1
30	11.0	11.8	0.55	-0.8
45	8.6	10.1	1.09	-1.5
60	6.9	8.48	1.15	-1.6
90	5.7	5.19	0.34	0.5

A simple equation was obtained from the Design Expert® model for remaining geosmin concentration predictions using the initial geosmin concentration, PAC dosage and selected contact time (for the values within: PAC concentrations of 5 to 30 mg/L, initial geosmin concentrations of 10 to 50 ng/L, and contact times of 15 to 90 minutes). The equation created by the 2FI model (that includes the interactions between the parameters) may guide the water utilities in quickly determining PAC dosages and contact times to best treat geosmin their source waters and is given below:

$$GSM_{out} = 4.391 - 0.275*PAC + 0.59*GSM_{in} - 0.0374*CT - 0.00961*PAC*GSM_{in} + 0.00234*PAC*CT - 0.0038*GSM_{in}*CT$$

where:

GSM_{out} = geosmin concentration remaining for the selected parameters (ng/L),

PAC = powdered activated carbon dose (mg/L),

GSM_{in} = geosmin concentration in the source water (ng/L), and

CT = contact time (min).

As can be observed from the equation, PAC, geosmin, and contact time are all important parameters in predicting the remaining geosmin concentration. Fig. 2.2 demonstrates how well the predicted and measured data correlate, as well as the contour plots for 15, 30, 45, 60, and 90 minutes to be used for prediction. The red data points (on Fig. 2.2. b-f) indicate the measured values for the remaining geosmin concentrations.

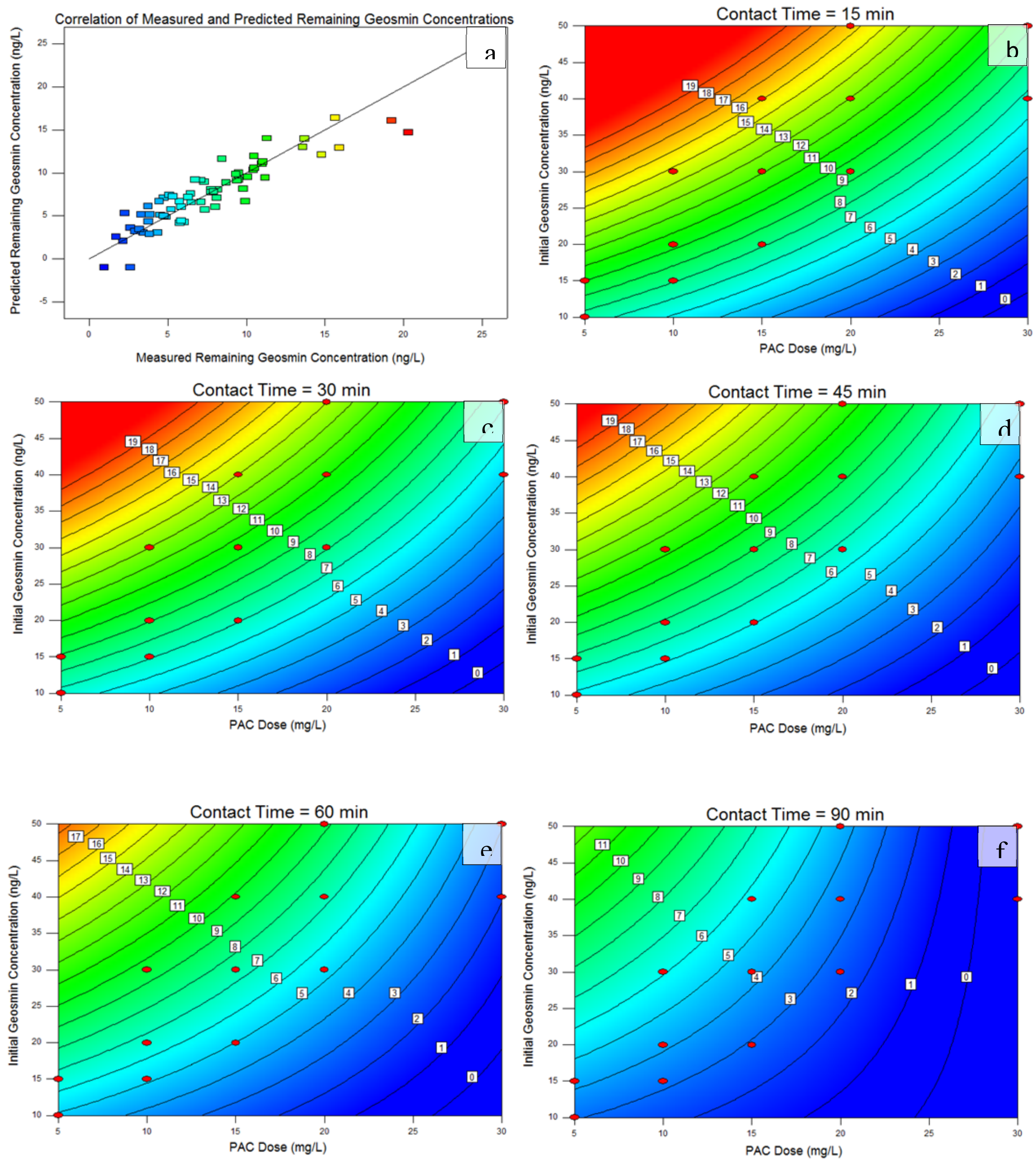

Figure 2.7: a. Plot of Predicted versus Measured Remaining Geosmin Concentrations, b-f. Predicted Geosmin Concentrations (contour lines) for Various Initial Geosmin and PAC concentrations over Selected Contact Times (red dots indicate the measured values)

The effect of TOC on geosmin removal efficiency by PAC was investigated with three PAC/geosmin combinations for a TOC level of 8 mg/L. Geosmin removal was 8 to 14% (or 1.6 to 2.8 ng/L) lower than that achieved with TOC levels of 3.76 mg/L. Table 2.6 shows the comparison between the geosmin remaining after 90 minutes contact time for average (~3.76 mg/L) and high TOC (8 mg/L) runs. The geosmin removal data for the average TOC samples for PAC 20 mg/L and geosmin 20 ng/L were obtained from the Design Expert® equation. The results indicate that the presence of higher TOC negatively affects the geosmin removal in all three combinations.

Table 2.6: Effects of increased TOC concentrations on Geosmin Removal

PAC Conc. (mg/L)	GSM Conc. (ng/L)	% Geosmin Removed		Geosmin Remaining (ng/L)	
		Avg. TOC	High TOC	Avg. TOC	High TOC
10	20	69	61	6.1	7.7
15	20	81	69	3.8	6.2
20	20	96	82	0.9	3.7

*Avg. TOC = ~3.76 mg/L, High TOC = 8 mg/L

4.2. Discussion

Results from this study are comparable to those found by previous researchers with similar water quality characteristics, contact times, PAC type and dosage, and initial geosmin concentrations. Bruce et al. (2002) reported 87% removal in geosmin at an initial geosmin concentration of 25 ng/L, PAC of 15 mg/L, and contact time of 4 hours; whereas the removal rates in this study showed a contact time of 90 minutes, PAC dosage of 15 mg/L and initial geosmin concentrations of 20 and 30 ng/L were determined to be 87.5 and 80.9%, respectively. The results are in agreement, even with the extended contact time for the Bruce et al. (2002); since it was shown in this study that the extended contact time only slightly increases removal. Additionally, dose response curves found by

Bruce et al. (2002), demonstrated that an increase in PAC dose will result in an increase in geosmin removal, as was shown by this study. The water quality parameters reported by Bruce et al. (2002) is similar to this study and averaged for pH at 8.22, temperature at 22.6 °C, turbidity at 4.2 NTU, and DOC at 2.57 mg/L. Also the contact times of 5, 10, 20, 60, and 240 minutes, PAC dosages between 1 to 50 mg/L, initial geosmin concentrations of 25 to 150 ng/L were tested in a laboratory setting. Although the initial geosmin concentrations vary from this one, the studies by Jung et al. (2004) and Ho et al. (2009) also confirm that an increase in PAC dosage improves geosmin removal. The study by Ho et al. (2009) used a coal based PAC at 30 mg/L, tested initial geosmin concentrations at 70-80 ng/L and contact times from 15 to 70 min. Compared to geosmin removal rates of 81 to 95% using the lignite coal based PAC at 30 mg/L, initial geosmin concentration at 50 ng/L, and contact times from 15 to 90 min tested by this study, the geosmin removal rates reported by Ho et al. (2009) as 60 to 95% are in agreement as well. Paralleling the findings by Jung et al. (2004) and Ho et al. (2009), this study also showed that the overall geosmin removal continues to slightly increase when contact time is increased from 30 to 90 minutes. Furthermore, Ho et al. (2009) found an increase of geosmin removal of about 20% when increasing contact time from 15 to 70 minutes. This is comparable to an increase of geosmin removal by 14 to 40% (depending on PAC dose and initial geosmin concentration) when the contact time was increased from 15 to 90 minutes for this study. Additionally, consistent with Ho et al (2009), geosmin removal rates are reduced by 10% when TOC levels are increased, indicating the organic matter affects adsorption of geosmin on to the PAC, though only minimally.

5. Conclusions

Tests conducted for this study demonstrated that PAC can be used to efficiently reduce geosmin levels to below odor threshold concentrations in finished drinking water. However, it should be noted that PAC/geosmin concentration combinations, and TOC levels affect the removal rates. It was found that 40 ng/L of geosmin is treated best at 90 minutes with 30 mg/L PAC, with most removal after 30 minutes. Additionally, 30 mg/L of PAC had the greatest removal rate across all time periods. Results from the three PAC/geosmin combinations for 8 mg/L TOC showed about a 6 to 14 % decrease in removal efficiency. This shows the selected PAC dose is affected minimally by the elevated levels of TOC at the tested combinations. It should be noted that more studies are required to further investigate the effects of TOC for a more reliable conclusion. Testing demonstrated that longer contact times do not greatly affect removal rates since the highest removal rate for all combinations occurred within the first 30 minutes of mixing. Design Expert® successfully predicted geosmin removal and the simple equation developed can help utilities to predict PAC dosing and to select a proper contact time. It should also be noted that as PAC dosages increase the frequency of backwashing filters or removing sludge from sedimentation basins will need to be increased to keep up with the accumulation of carbon.

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APPENDIX A: RESULTS OBTAINED FROM TESTING

I. Run 1: PAC 5 mg/L and Geosmin 10 ng/L

Table B.1: Control Values for Replicate 1

Control	Area	Conc.
1	19036	8.02
30	17420	7.34
60	18521	7.80
120	15038	6.33

Table B.2: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 2	Conc. 2	Avg.	Std. Dev.
1	20836	20173	8.78	8.50	8.64	0.20
15	16900	17198	7.12	7.24	7.18	0.09
30	14201	13571	5.98	5.72	5.85	0.19
45	12298	12284	5.18	5.17	5.18	0.00
60	12276	12262	5.17	5.17	5.17	0.00
90	10035	11041	4.23	4.65	4.44	0.30
120	9955	9938	4.19	4.19	4.19	0.01

Table B.3: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	4319
5	13637
10	27599
25	57376

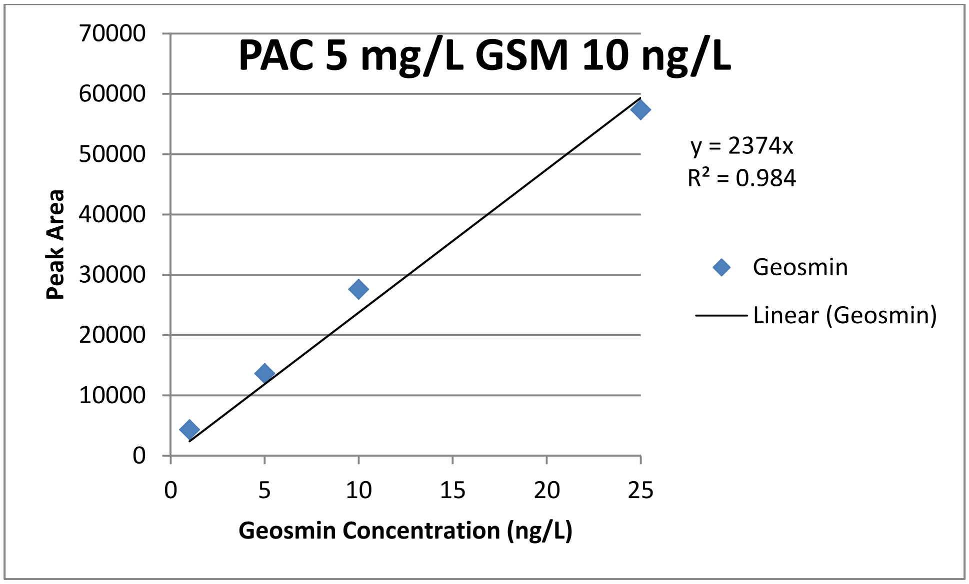


Figure B.1: Standard Curve for Replicate 1

Table B.4: Control Values for Replicate 2

Control	Area	Conc.
1	16487	6.94
30	23155	9.75
60	23053	9.71
120	20698	8.72

Table B.5: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	17965	17749	7.57	7.48	7.52	0.06
15	14253	14170	6.00	5.97	5.99	0.02
30	11791	13150	4.97	5.54	5.25	0.40
45	11442	11450	4.82	4.82	4.82	0.00
60	11250	11590	4.74	4.88	4.81	0.10
90	10336	10467	4.35	4.41	4.38	0.04
120	11153	10588	4.70	4.46	4.58	0.17

Table B.6: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	4319
5	13637
10	27599
25	57376

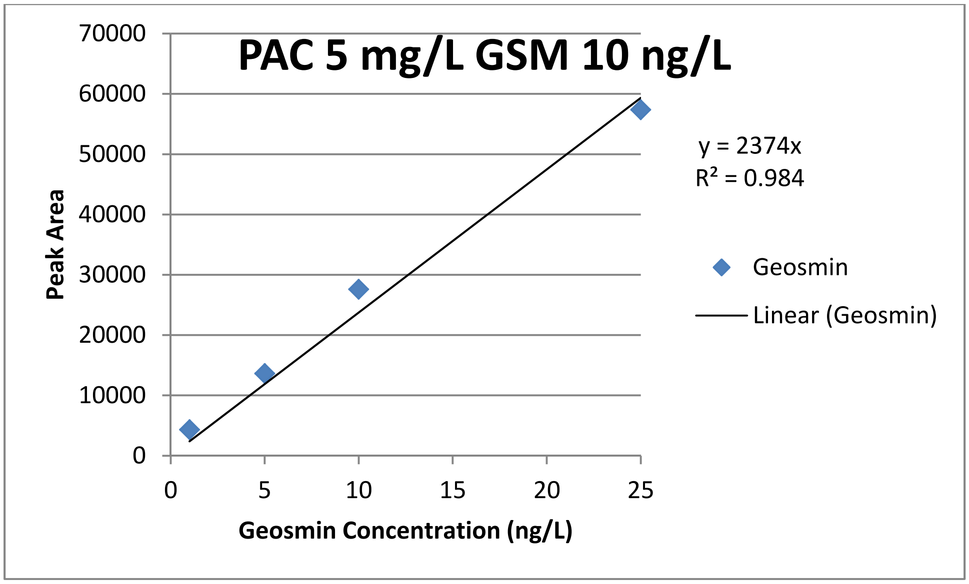


Figure B.2: Standard Curve for Replicate 2

Table B.7: Control Values for Replicate 3

Control	Area	Conc.
1	26702	9.97
30	22842	8.53
60	23514	8.78
120	26686	9.97

Table B.8: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	21109	19382	7.88	7.24	7.56	0.46
15	16600	16626	6.20	6.21	6.20	0.01
30	16506	16259	6.16	6.07	6.12	0.07
45	15425	14655	5.76	5.47	5.62	0.20
60	12962	11816	4.84	4.41	4.63	0.30
90	11078	11691	4.14	4.37	4.25	0.16
120	11398	10814	4.26	4.04	4.15	0.15

Table B.9: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	2409
5	12487
10	24575
25	68017

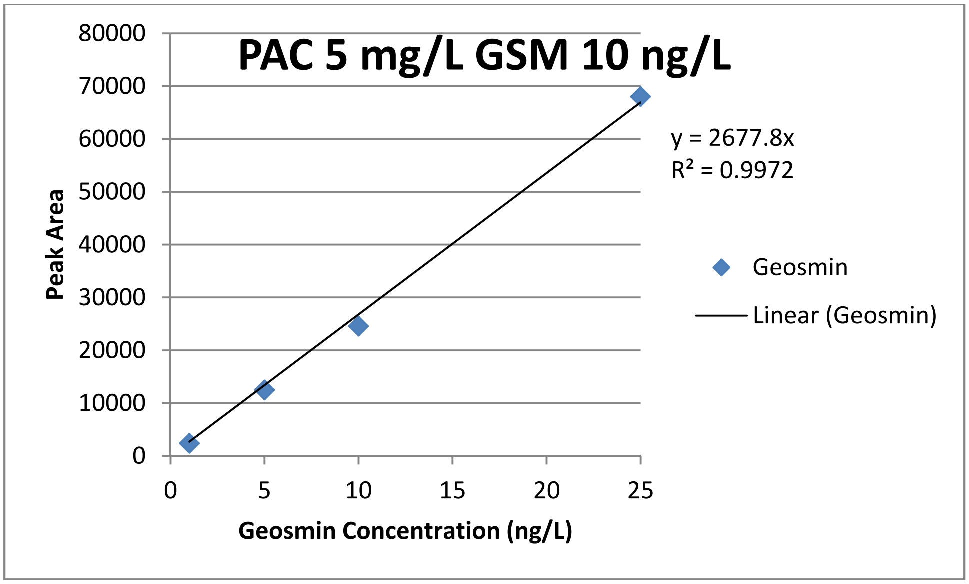


Figure B.3: Standard Curve for Replicate 3

Table B.10: Percent Removed for Run 1

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	4	23	24	17.1	11.3
15	20	39	38	32.3	10.4
30	35	46	39	40.0	5.6
45	42	51	44	45.6	4.3
60	43	51	54	49.0	5.8
90	51	55	57	54.4	3.5
120	53	53	59	55.0	3.1

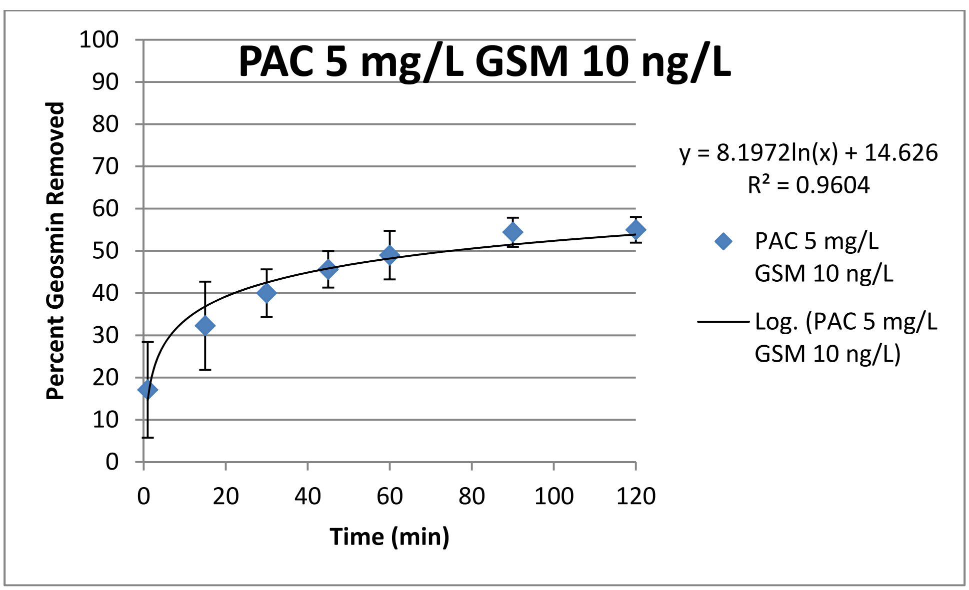


Figure B.4: Percent removed for Run 1

Table B.11: Concentration Remaining for Run 1

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	8.64	7.52	7.56	7.9	0.6
15	7.18	5.99	6.20	6.5	0.6
30	5.85	5.25	6.12	5.7	0.4
45	5.18	4.82	5.62	5.2	0.4
60	5.17	4.81	4.63	4.9	0.3
90	4.44	4.38	4.25	4.4	0.1
120	4.19	4.58	4.15	4.3	0.2

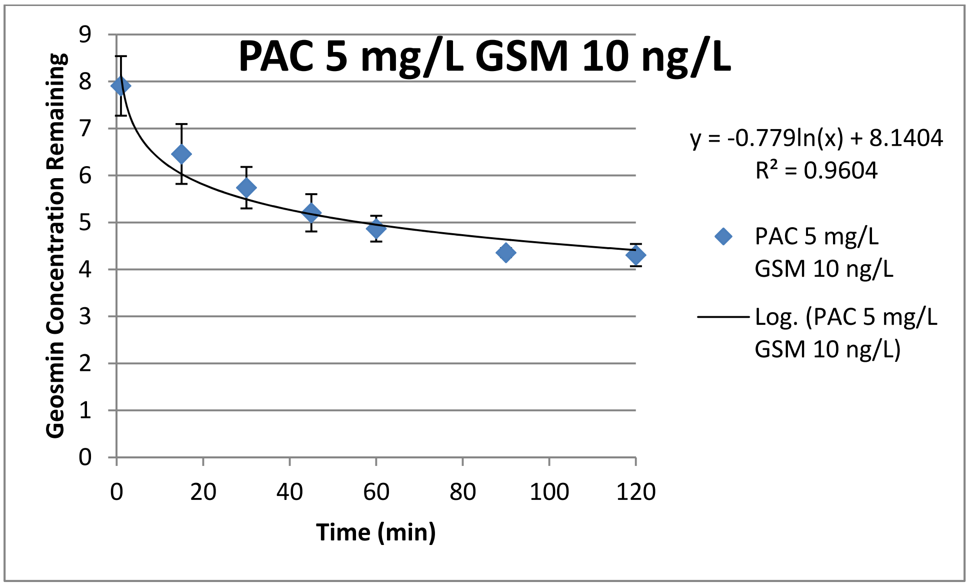


Figure B.5: Concentration Remaining for Run 1

Table B.12: Water Quality for Run 1

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Average	
Temp	17	18	16	17	°C
pH	7.72	7.7	7.76	7.7	
DO	8.1	8.6	9.65	8.8	mg/L
Turbidity	4.45	3.52	2.39	3.5	NTU
Conductivity	77	348	75.8	166.9	µs/cm
TOC	3.90	3.90	3.89	3.90	mg/L

II. Run 2: PAC 5 mg/L and Geosmin 15 ng/L

Table B.13: Control Values for Replicate 1

Control	Area	Conc.
1	10028	12.52
30	11796	14.73
60	11825	14.77
90	11807	14.74

Table B.14: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	9278	9153	11.59	11.43	11.51	0.11
15	7597	7649	9.49	9.55	9.52	0.05
30	7100	7040	8.87	8.79	8.83	0.05
45	6417	6210	8.01	7.75	7.88	0.18
60	5203	5430	6.50	6.78	6.64	0.20
90	4798	4966	5.99	6.20	6.10	0.15

Table B.15: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	1873
5	4993
10	9221
25	19295

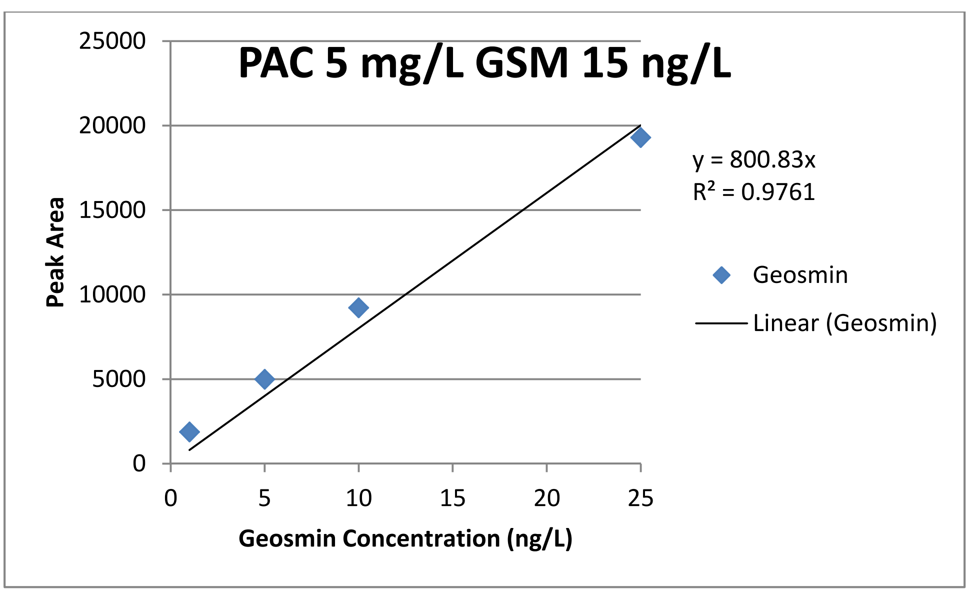


Figure B.6: Standard Curve for Replicate 1

Table B.16: Control Values for Replicate 2

Control	Area	Conc.
1	11960	14.93
30	11343	14.16
60	11738	14.66
90	11548	14.42

Table B.17: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	9477	9552	11.83	11.93	11.88	0.07
15	7663	7359	9.57	9.19	9.38	0.27
30	7193	6901	8.98	8.62	8.80	0.26
45	5824	6181	7.27	7.72	7.50	0.32
60	5020	4927	6.27	6.15	6.21	0.08
90	4693	4820	5.86	6.02	5.94	0.11

Table B.18: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	1873
5	4993
10	9221
25	19295

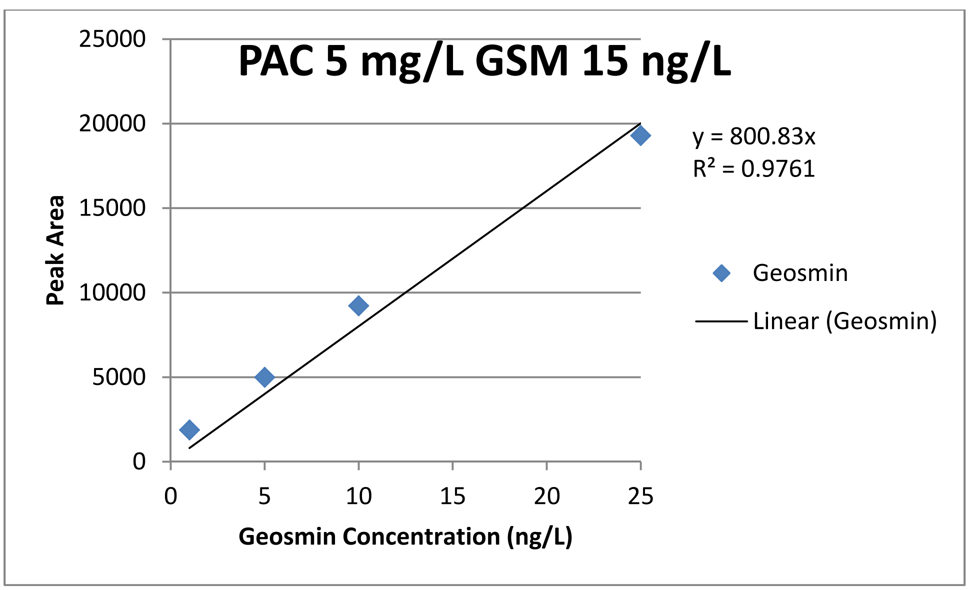


Figure B.7: Standard Curve for Replicate 2

Table B.19: Control Values Replicate 3

Control	Area	Conc.
1	11798	14.64
30	11912	14.87
60	11352	14.18
90	12022	15.01

Table B.20: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	9223	9527	11.52	11.90	11.71	0.27
15	7817	7614	9.76	9.51	9.63	0.18
30	6778	6875	8.46	8.58	8.52	0.09
45	6390	6177	7.98	7.71	7.85	0.19
60	5300	5366	6.62	6.70	6.66	0.06
90	4924	4719	6.15	5.89	6.02	0.18

Table B.21: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	2092
5	3997
10	7007
25	20520

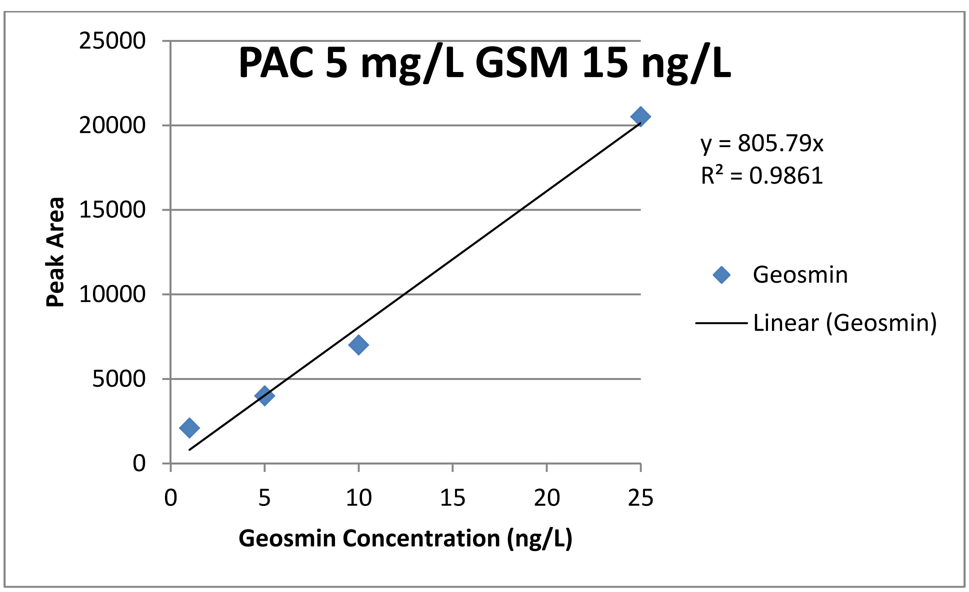


Figure B.8: Standard Curve for Replicate 3

Table B.22: Percent Removed for Run 2

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	23	21	22	22.0	1.2
15	37	37	36	36.6	0.9
30	41	41	43	41.9	1.1
45	47	50	48	48.4	1.4
60	56	59	56	56.6	1.7
90	59	60	60	59.9	0.5

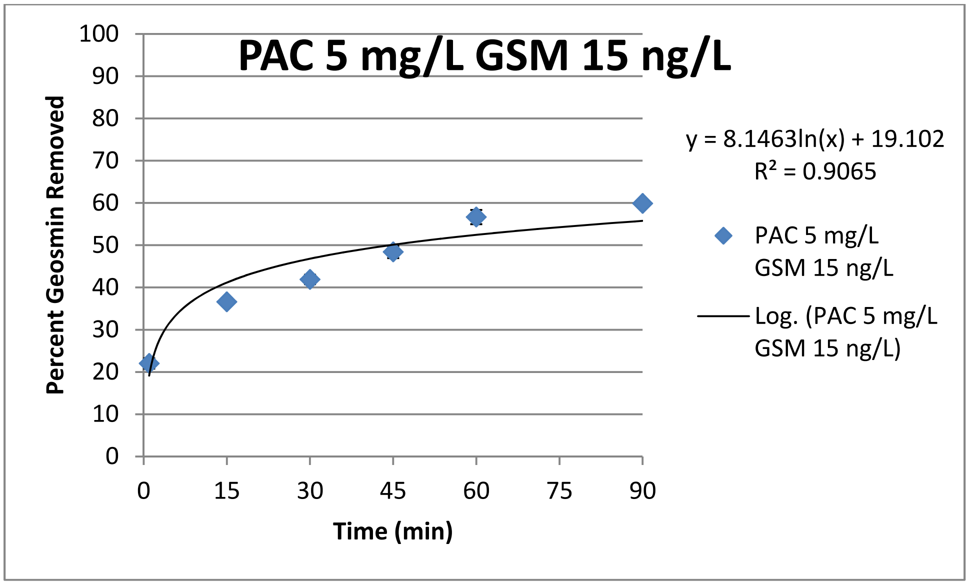


Figure B.9: Percent Removed for Run 2

Table B.23: Concentration Remaining

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	11.51	11.88	11.71	11.7	0.2
15	9.52	9.38	9.63	9.5	0.1
30	8.83	8.80	8.52	8.7	0.2
45	7.88	7.50	7.85	7.7	0.2
60	6.64	6.21	6.66	6.5	0.3
90	6.10	5.94	6.02	6.0	0.1

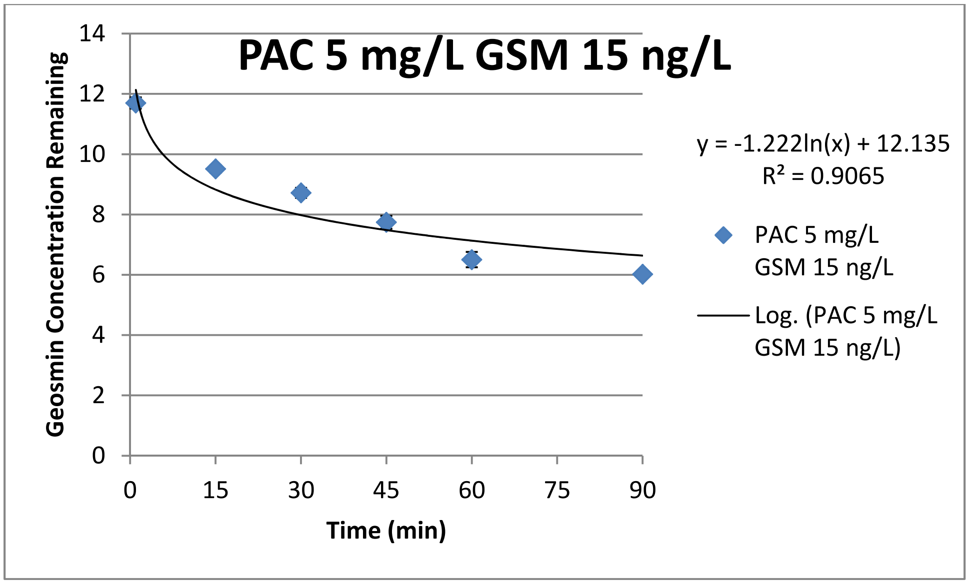


Figure B.10: Concentration Remaining for Run 2

Table B.24: Water Quality for Run 2

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	16	16	15	15.7	°C
pH	7.5	7.4	7.4	7.4	
DO	8.6	8.5	8.4	8.5	mg/L
Turbidity	3.35	3.18	2.97	3.2	NTU
Conductivity	73	74	73	73.3	µs/cm
TOC	3.66	3.66	3.66	3.66	mg/L

III. Run 3: PAC 10 mg/L and Geosmin 15 ng/L

Table B.25: Control Values Replicate 1

Control	Area	Conc.
1	12550	15.25
30	12129	14.74
60	12338	15.00
90	12294	14.94

Table B.26: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	9035	9660	10.98	11.74	11.36	0.54
15	6758	6944	8.21	8.44	8.33	0.16
30	3762	3784	4.57	4.60	4.59	0.02
45	3119	3259	3.79	3.96	3.88	0.12
60	2713	2865	3.30	3.48	3.39	0.13
90	2546	2275	3.09	2.77	2.93	0.23

Table B.27: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	924
5	3933
10	9240
25	20194

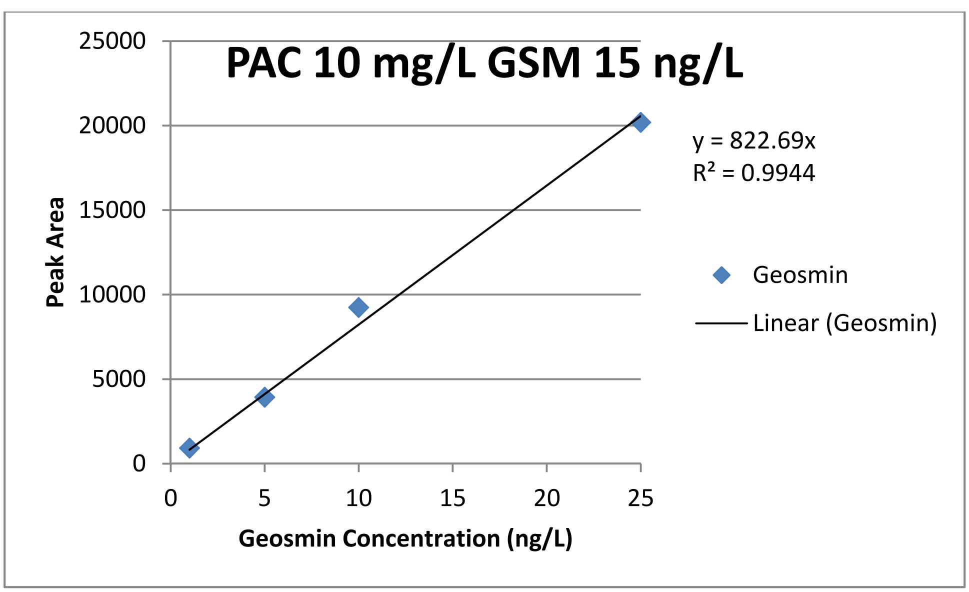


Figure B.11: Standard Curve for Replicate 1

Table B.28: Control Values for Replicate 2

Control	Area	Conc.	TCA
1	13003	14.95	7178
30	12361	14.22	7264
60	12543	14.42	7127
90	12392	14.25	7458

Table B.29: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	8694	9342	10.00	10.74	10.37	0.53
15	7228	7021	8.31	8.07	8.19	0.17
30	4070	4052	4.68	4.66	4.67	0.01
45	3271	3306	3.76	3.80	3.78	0.03
60	2973	2882	3.42	3.31	3.37	0.07
90	2619	2423	3.01	2.79	2.90	0.16

Table B.30: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	1049
5	5459
10	9485
25	21194

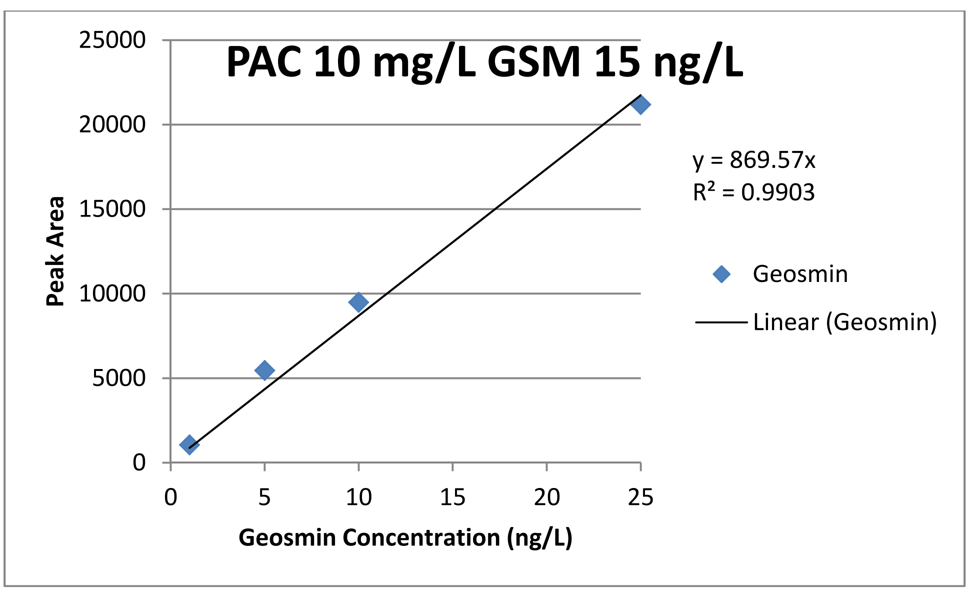


Figure B.12: Standard Curve for Replicate 2

Table B.31: Control Values for Replicate 3

Control	Area	Conc.
1	12664	14.66
30	12434	14.40
60	12452	14.42
90	12766	14.78

Table B.32: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	8577	8276	9.93	9.58	9.76	0.25
15	7055	6787	8.17	7.86	8.01	0.22
30	4244	4318	4.91	5.00	4.96	0.06
45	3179	3034	3.68	3.51	3.60	0.12
60	2809	2603	3.25	3.01	3.13	0.17
90	2462	2681	2.85	3.10	2.98	0.18

Table B.33: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	723
5	4119
10	8330
25	21757

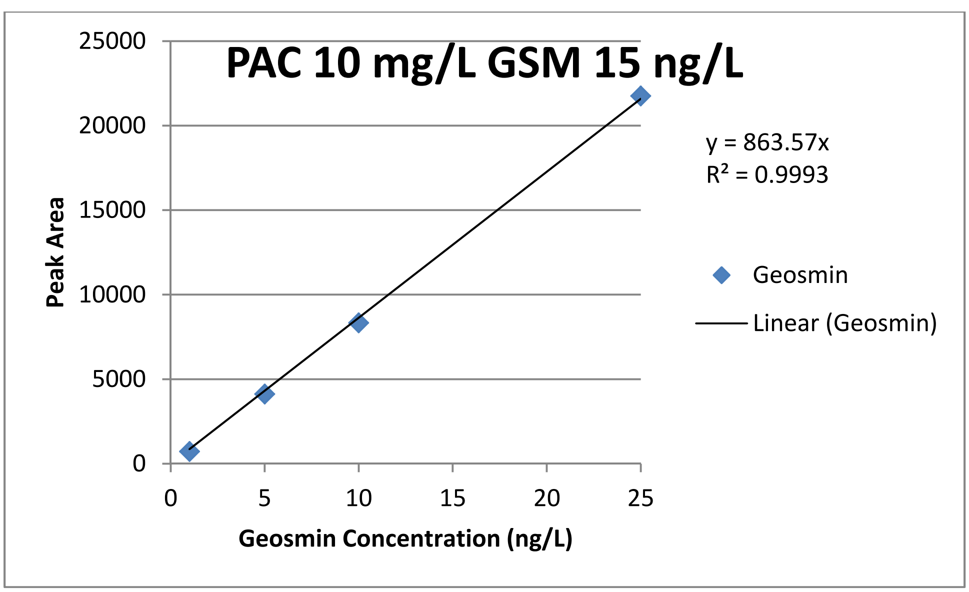


Figure B.13: Standard Curve for Replicate 3

Table B.34: Percent Removed for Run 3

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	24	31	35	30.0	5.4
15	44	45	47	45.5	1.0
30	69	69	67	68.4	1.3
45	74	75	76	75.0	0.9
60	77	78	79	78.0	0.9
90	80	81	80	80.4	0.3

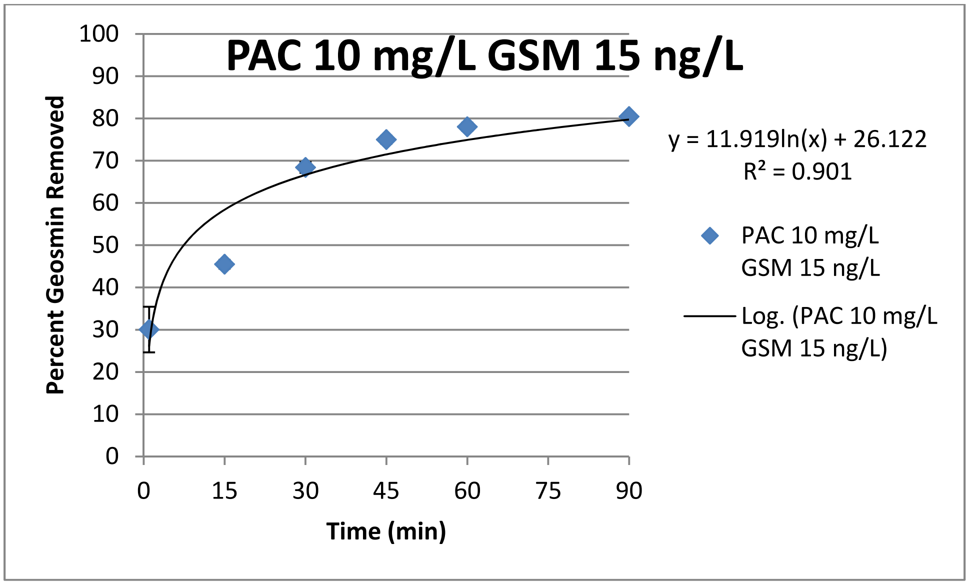


Figure B.14: Percent Removed for Run 3

Table B.35: Concentration Remaining for Run 3

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	11.36	10.37	9.76	10.5	0.8
15	8.33	8.19	8.01	8.2	0.2
30	4.59	4.67	4.96	4.7	0.2
45	3.88	3.78	3.60	3.8	0.1
60	3.39	3.37	3.13	3.3	0.1
90	2.93	2.90	2.98	2.9	0.0

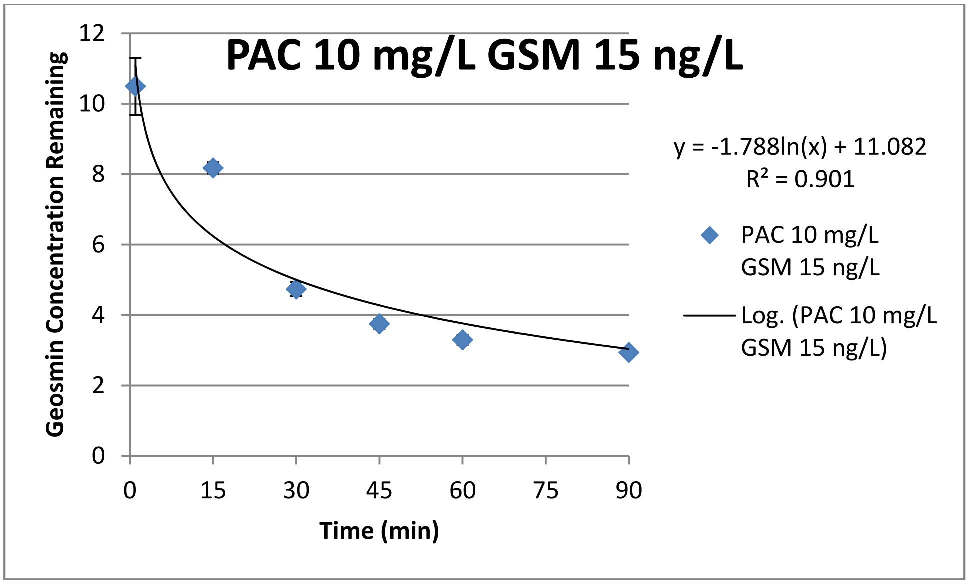


Figure B.15: Concentration Remaining for Run 3

Table B.36: Water Quality for Run 3

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	15	15	15	15	°C
pH	7.6	7.5	7.5	7.5	
DO	9.1	8.9	8.9	9.0	mg/L
Turbidity	2.38	2.56	2.56	2.5	NTU
Conductivity	74	75	75	74.7	µs/cm
TOC	3.37	3.37	3.37	3.37	mg/L

IV. Run 4: PAC 10 mg/L and Geosmin 20 mg/L

Table B.37: Control Values for Replicate 1

Control	Area	Conc.
1	46015	19.38
30	46798	19.71
60	45694	19.25
120	45563	19.19

Table B.38: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	42610	42708	17.95	17.99	17.97	0.03
15	26438	26500	11.14	11.16	11.15	0.02
30	23000	23168	9.69	9.76	9.72	0.05
45	18025	22139	7.59	9.33	8.46	1.23
60	17622	19010	7.42	8.01	7.72	0.41
90	14684	18055	6.19	7.61	6.90	1.00
120	13502	16033	5.69	6.75	6.22	0.75

Table B.39: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	4319
5	13637
10	27599
25	57376

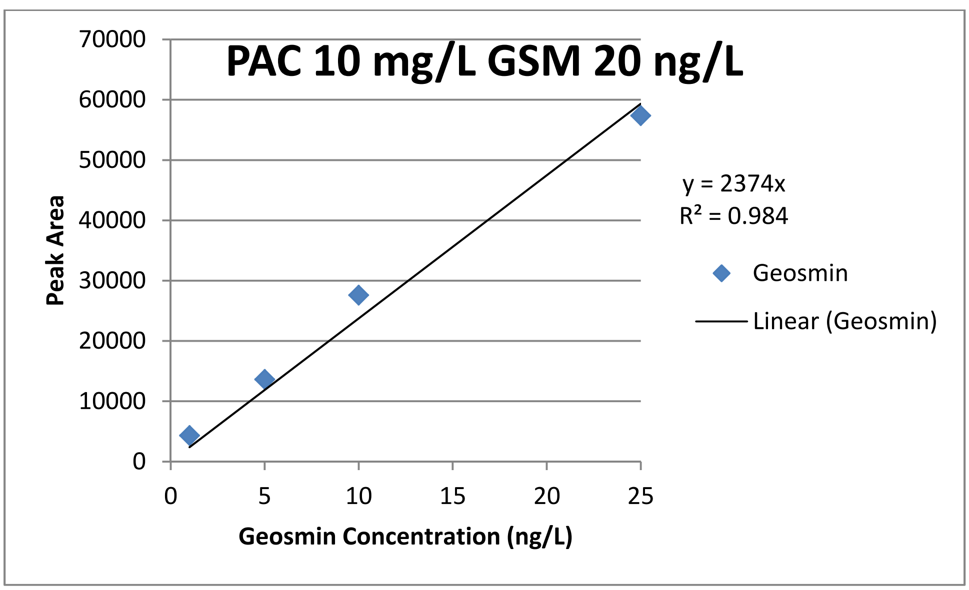


Figure B.16: Standard Curve for Replicate 1

Table B.40: Control Values for Replicate 2

Control	Area	Conc.
1	44665	18.99
30	44541	18.94
60	43766	18.61
120	44293	18.83

Table B.41: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	31794	34544	13.52	14.69	14.10	0.83
15	24331	26281	10.34	11.17	10.76	0.59
30	23310	23500	9.91	9.99	9.95	0.06
45	17980	18149	7.64	7.72	7.68	0.05
60	15869	15286	6.75	6.50	6.62	0.18
90	10658	11860	4.53	5.04	4.79	0.36
120	10638	11342	4.52	4.82	4.67	0.21

Table B.42: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	3344
5	16369
10	27106
25	56403

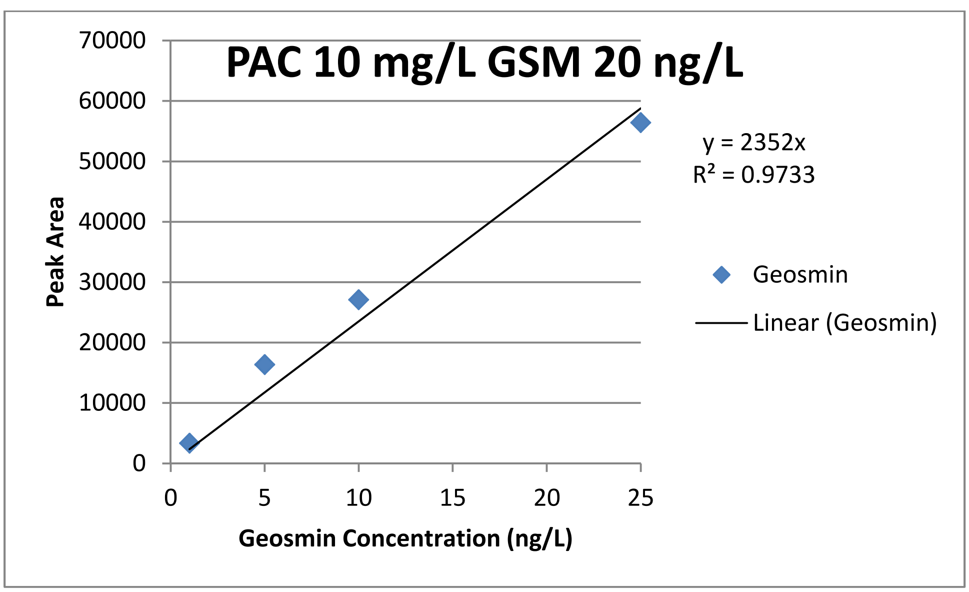


Figure B.17: Standard Curve for Replicate 2

Table B.43: Control Values for Replicate 3

Control	Area	Conc.
1	5229	16.18
30	5542	17.15
60	5547	17.16
120	5504	17.03

Table B.44: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	4515	4483	13.97	13.87	13.92	0.07
15	3032	3036	9.38	9.39	9.39	0.01
30	2767	2753	8.56	8.52	8.54	0.03
45	2471	2463	7.64	7.62	7.63	0.02
60	2278	2243	7.05	6.94	6.99	0.08
90	1791	1834	5.54	5.67	5.61	0.09
120	1559	1675	4.82	5.18	5.00	0.25

Table B.45: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	487
5	1595
10	3419
25	8004

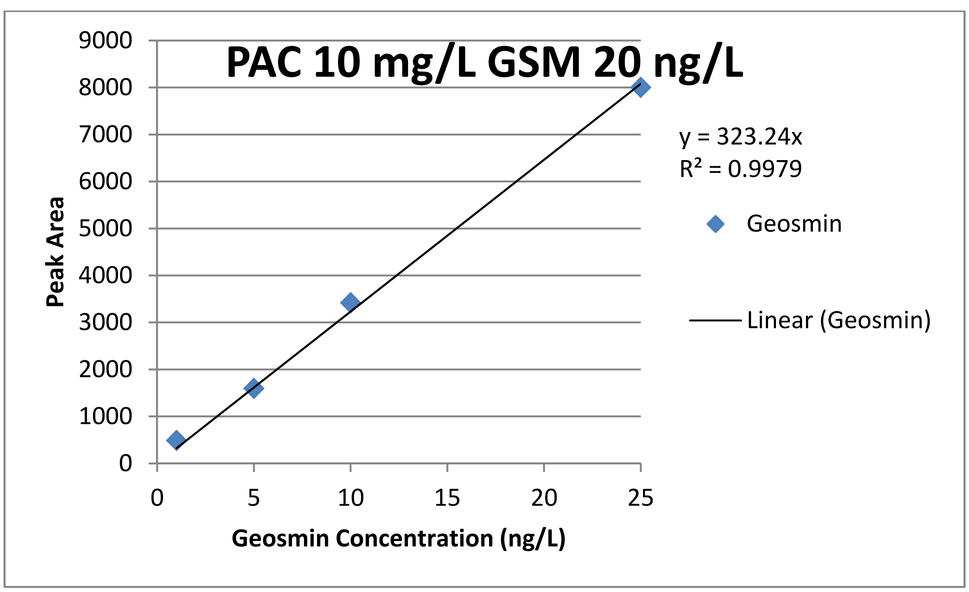


Figure B.18: Standard Curve for Replicate 3

Table B.46: Percent Removed for Run 4

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	9	26	20	18.4	8.7
15	43	43	46	44.4	1.7
30	51	48	51	49.8	1.9
45	57	60	56	57.7	1.7
60	61	65	60	62.0	2.7
90	65	75	68	69.3	5.0
120	68	75	71	71.8	3.5

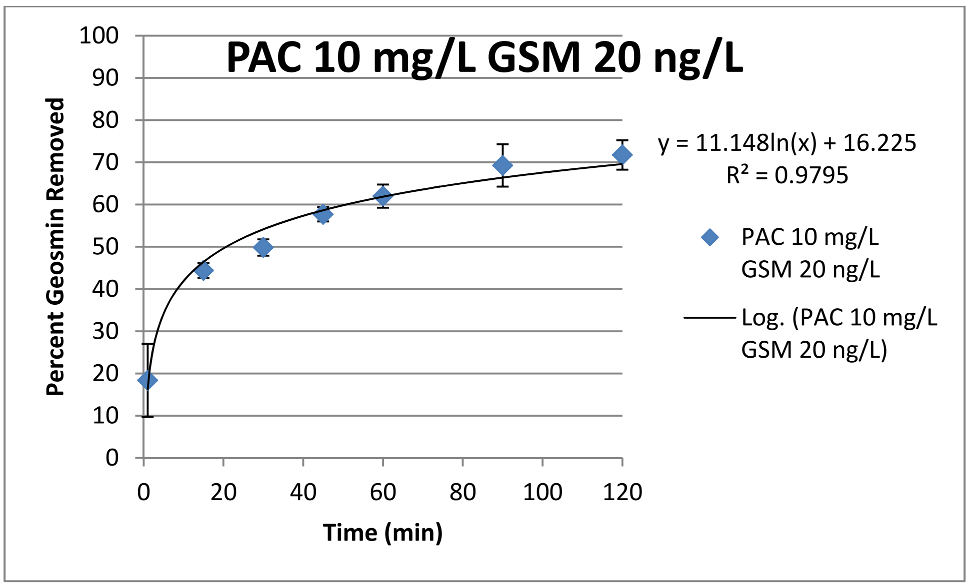


Figure B.19: Percent Removed for Run 4

Table B.47: Concentration Remaining for Run 4

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	17.97	14.10	13.92	15.3	2.3
15	11.15	10.76	9.39	10.4	0.9
30	9.72	9.95	8.54	9.4	0.8
45	8.46	7.68	7.63	7.9	0.5
60	7.72	6.62	6.99	7.1	0.6
90	6.90	4.79	5.61	5.8	1.1
120	6.22	4.67	5.00	5.3	0.8

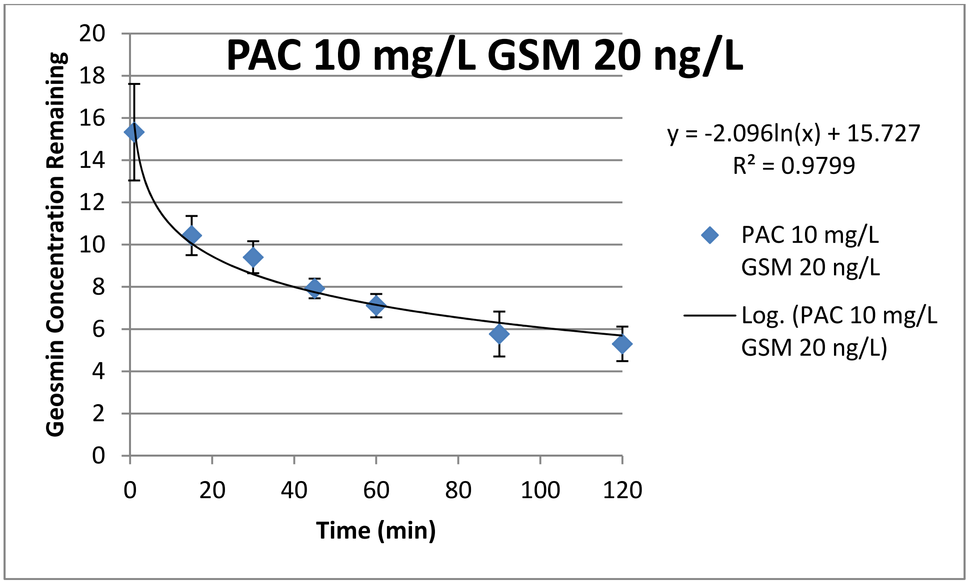


Figure B.20: Concentration Remaining for Run 4

Table B.48: Water Quality for Run 4

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	16	18	16	17	°C
pH	7.5	7.8	7.7	7.7	
DO	8.4	9.46	9.76	9.2	mg/L
Turbidity	4.12	3.29	2.24	3.2	NTU
Conductivity	77.5	107	76	86.8	µs/cm
TOC	3.90	3.85	3.82	3.86	mg/L

V. Run 5: PAC 10 mg/L and Geosmin 30 ng/L

Table B.49: Control Values for Replicate 1

Control	Area	Conc.
1	24263	30.12
30	23095	28.67
60	22873	28.39
90	23786	29.53

Table B.50: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	19681	19367	24.43	24.04	24.24	0.28
15	16434	15717	20.40	19.51	19.96	0.63
30	11586	11107	14.38	13.79	14.09	0.42
45	8895	8484	11.04	10.53	10.79	0.36
60	8063	7358	10.01	9.13	9.57	0.62
90	5931	5526	7.36	6.86	7.11	0.36

Table B.51: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	722
5	2183
10	6599
25	21094

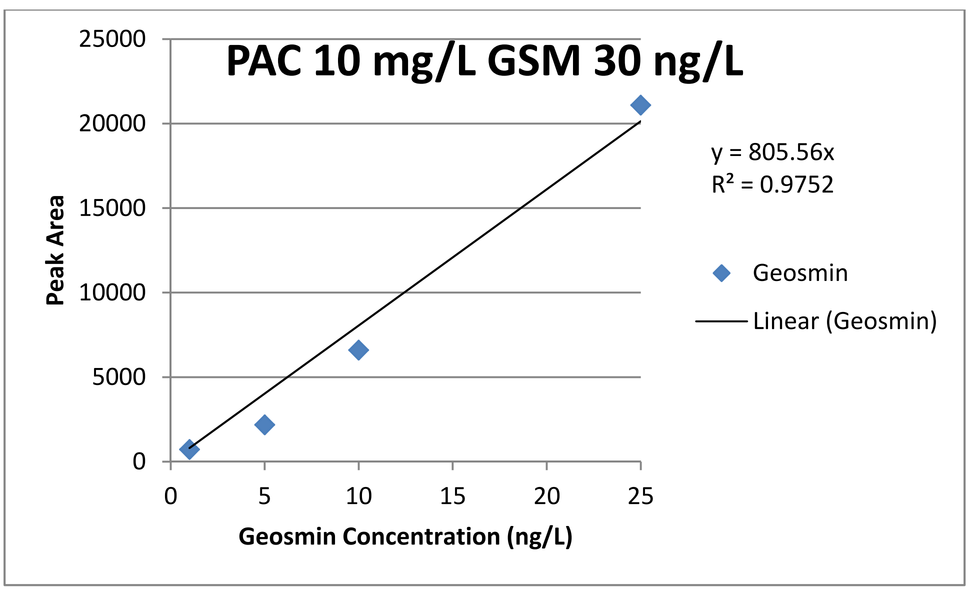


Figure B.21: Standard Curve for Replicate 1

Table B.52: Control Values for Replicate 2

Control	Area	Conc.
1	19889	28.85
30	20127	29.20
60	19714	28.60
90	19432	28.19

Table B.53: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	18132	17951	26.30	26.04	26.17	0.19
15	13437	13778	19.49	19.99	19.74	0.35
30	7399	7279	10.73	10.56	10.65	0.12
45	6595	6839	9.57	9.92	9.74	0.25
60	6107	6470	8.86	9.39	9.12	0.37
90	4721	4922	6.85	7.14	6.99	0.21

Table B.54: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	504
5	4081
10	7253
25	16971

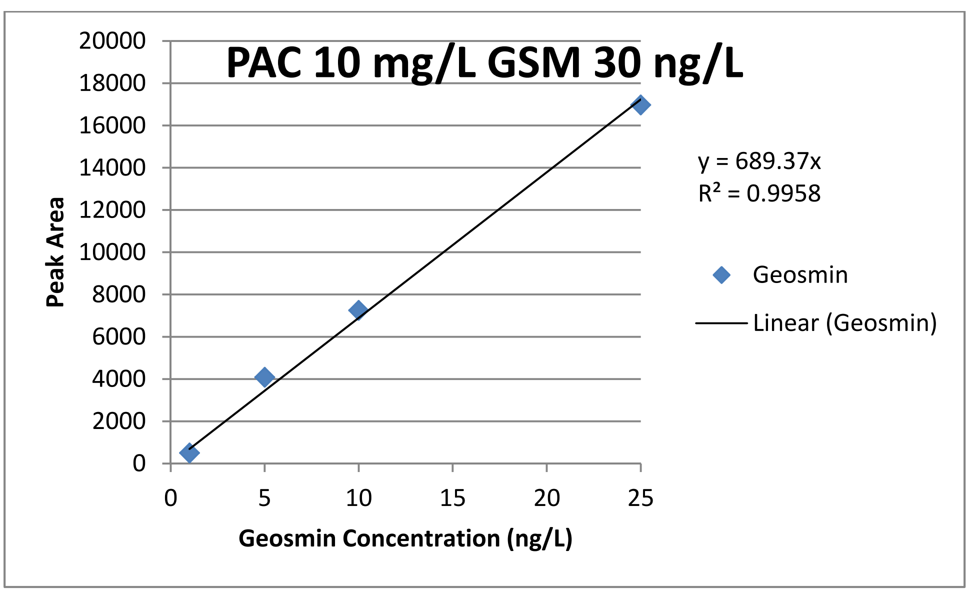


Figure B.22: Standard Curve for Replicate 2

Table B.55: Control Values for Replicate 3

Control	Area	Conc.
1	19274	31.68
30	19726	32.42
60	13168	21.64
90	19488	32.03

Table B.56: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	17911	17648	29.44	29.01	29.22	0.31
15	12644	13155	20.78	21.62	21.20	0.59
30	9493	9983	15.60	16.41	16.01	0.57
45	7437	7850	12.22	12.90	12.56	0.48
60	6882	7208	11.31	11.85	11.58	0.38
90	5764	6395	9.47	10.51	9.99	0.73

Table B.57: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	1105
5	3956
10	6797
25	14723

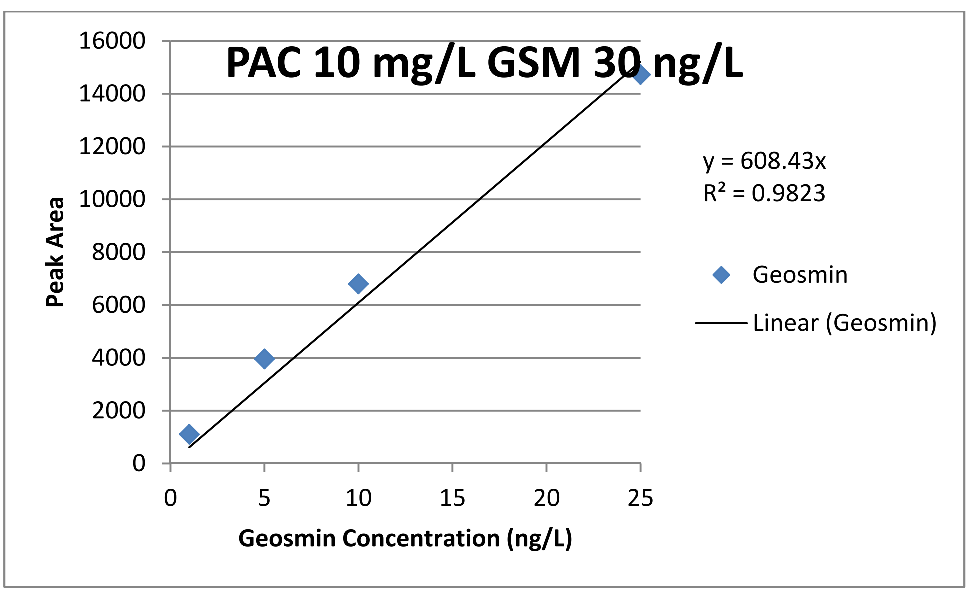


Figure B.23: Standard Curve for Replicate 3

Table B.58: Percent Removed for Run 5

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	19	10	9	12.5	5.8
15	33	32	34	33.1	1.0
30	53	63	50	55.4	7.0
45	64	66	61	63.7	2.8
60	68	69	64	66.8	2.6
90	76	76	69	73.7	4.2

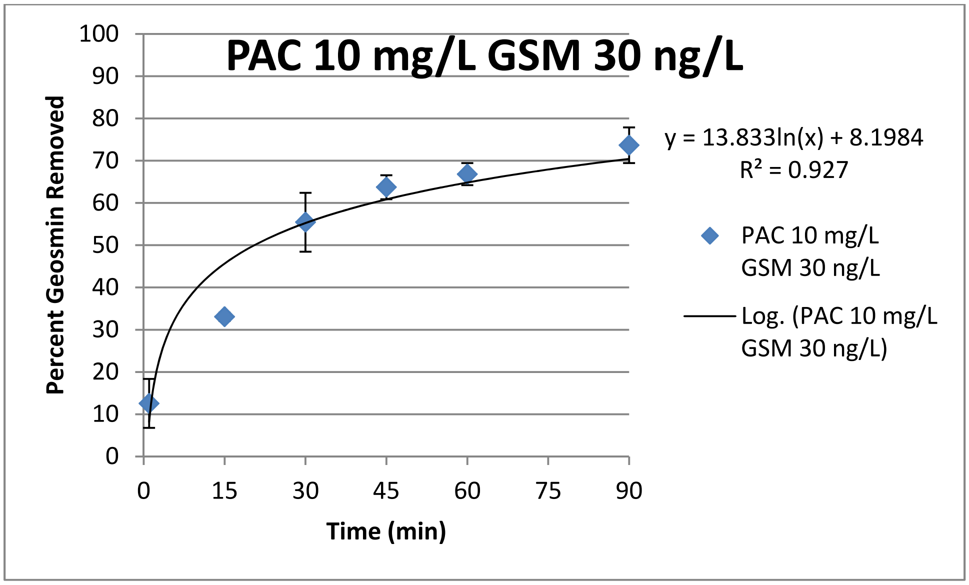


Figure B.24: Percent Removed for Run 5

Table B.59: Concentration Remaining for Run 5

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	24.24	26.17	29.22	26.5	2.5
15	19.96	19.74	21.20	20.3	0.8
30	14.09	10.65	16.01	13.6	2.7
45	10.79	9.74	12.56	11.0	1.4
60	9.57	9.12	11.58	10.1	1.3
90	7.11	6.99	9.99	8.0	1.7

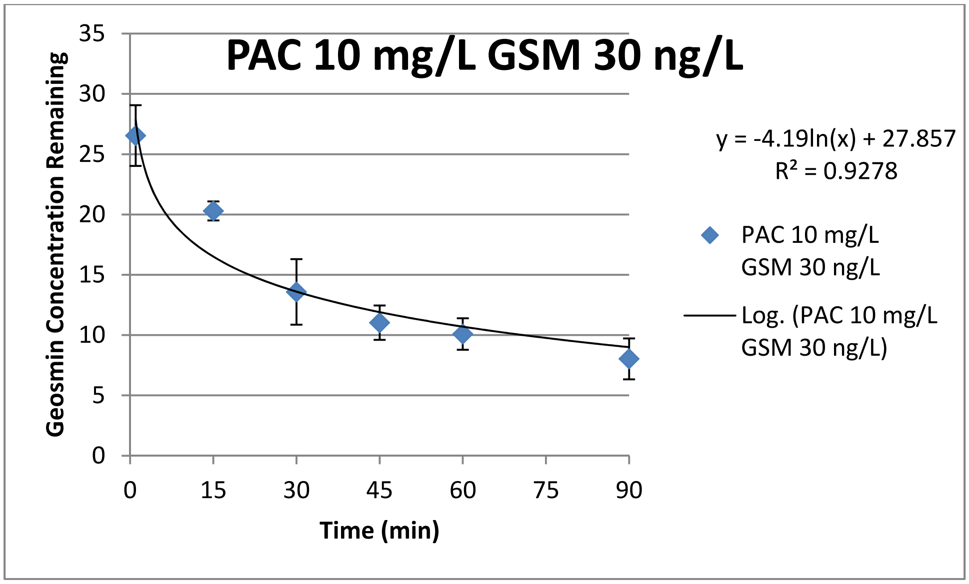


Figure B.25: Concentration Remaining for Run 5

Table B.60: Water Quality for Run 5

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	15	15	15	15	°C
pH	7.4	7.4	7.5	7.4	
DO	9.3	9.4	9.5	9.4	mg/L
Turbidity	2.18	2.18	2.14	2.2	NTU
Conductivity	77	79	75	77.0	µs/cm
TOC	3.78	3.78	3.81	3.79	mg/L

VI. Run 6: PAC 15 mg/L and Geosmin 20 ng/L

Table B.61: Control Values for Replicate 1

Control	Area	Conc.
1	17010	20.68
30	16523	20.08
60	16353	19.88
90	16294	19.81

Table B.62: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	11689	11553	14.21	14.04	14.13	0.12
15	8279	7819	10.06	9.50	9.78	0.40
30	6551	6659	7.96	8.09	8.03	0.09
45	4918	4974	5.98	6.05	6.01	0.05
60	3986	4060	4.85	4.94	4.89	0.06
90	3237	3287	3.93	4.00	3.97	0.04

Table B.63: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	924
5	3933
10	9240
25	20194

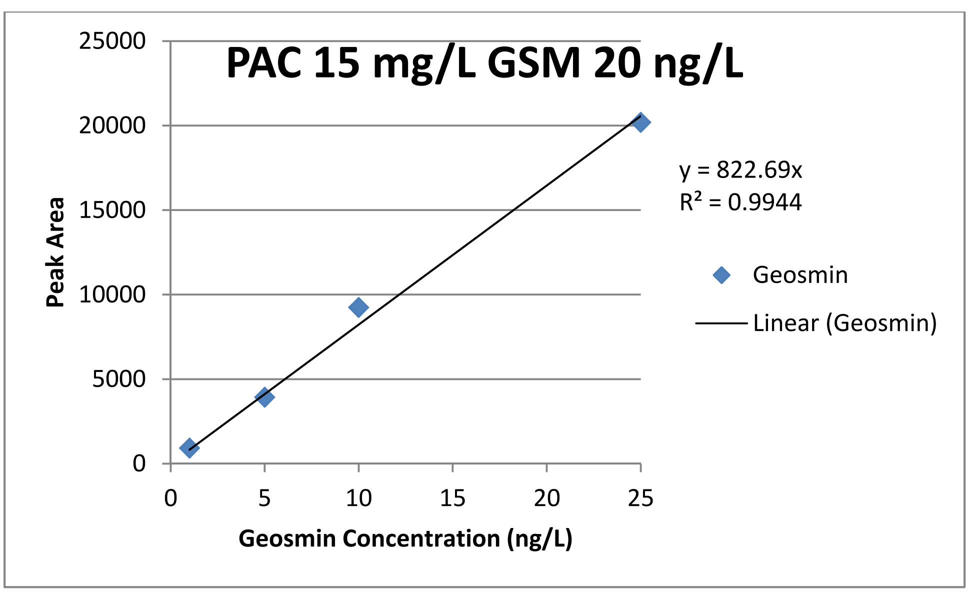


Figure B.26: Standard Curve for Replicate 1

Table B.64: Control Values for Replicate 2

Control	Area	Conc.
1	17373	19.98
30	17139	19.71
60	17140	19.71
90	17267	19.86

Table B.65: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	14584	14300	16.77	16.44	16.61	0.23
15	8480	8698	9.75	10.00	9.88	0.18
30	7031	7094	8.09	8.16	8.12	0.05
45	4820	5302	5.54	6.10	5.82	0.39
60	4172	4200	4.80	4.83	4.81	0.02
90	3428	3506	3.94	4.03	3.99	0.06

Table B.66: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	1049
5	5459
10	9485
25	21194

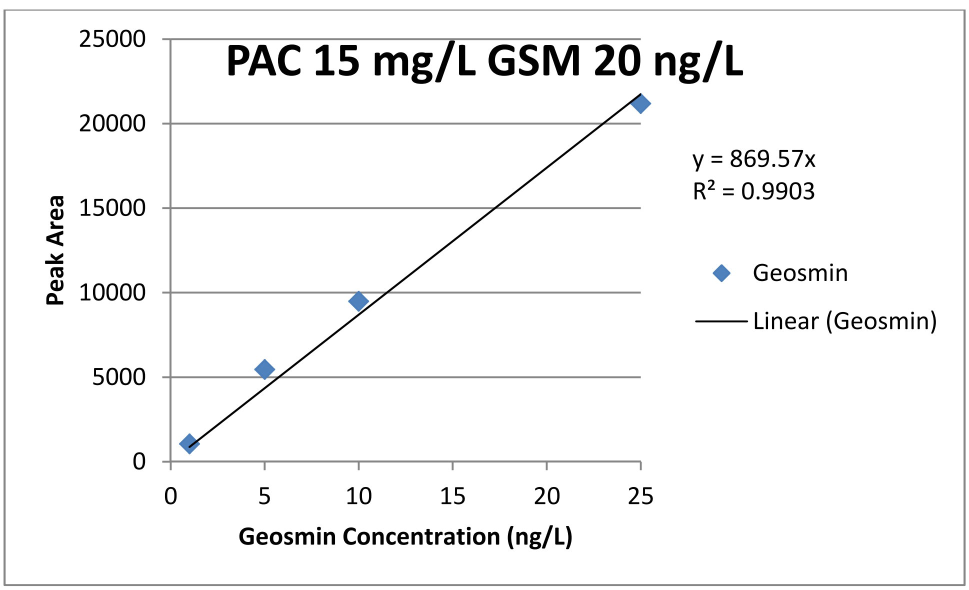


Figure B.27: Standard Curve for Replicate 2

Table B.67: Control Values for Replicate 3

Control	Area	Conc.
1	16854	19.52
30	17000	19.69
60	16470	19.07
90	16778	19.43

Table B.68: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	14367	13693	16.64	15.86	16.25	0.55
15	8185	8589	9.48	9.95	9.71	0.33
30	7029	7080	8.14	8.20	8.17	0.04
45	5066	4838	5.87	5.60	5.73	0.19
60	4126	3636	4.78	4.21	4.49	0.40
90	3130	2963	3.62	3.43	3.53	0.14

Table B.69: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	723
5	4119
10	8330
25	21757

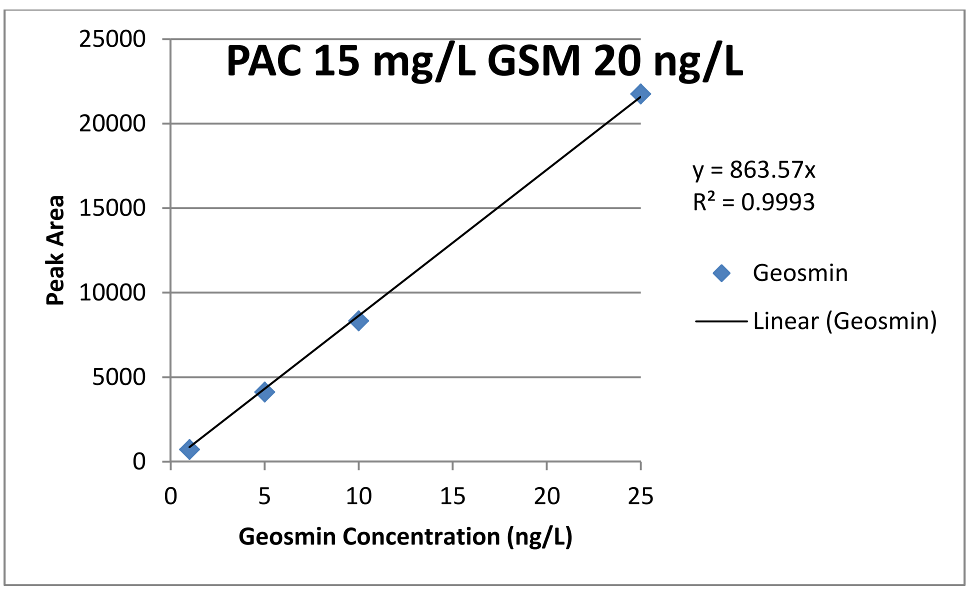


Figure B.28: Standard Curve for Replicate 3

Table B.70: Percent Removed for Run 6

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	29	17	19	21.7	6.7
15	51	51	51	51.0	0.4
30	60	59	59	59.5	0.4
45	70	71	71	70.7	0.7
60	76	76	78	76.3	1.1
90	80	80	82	80.9	1.3

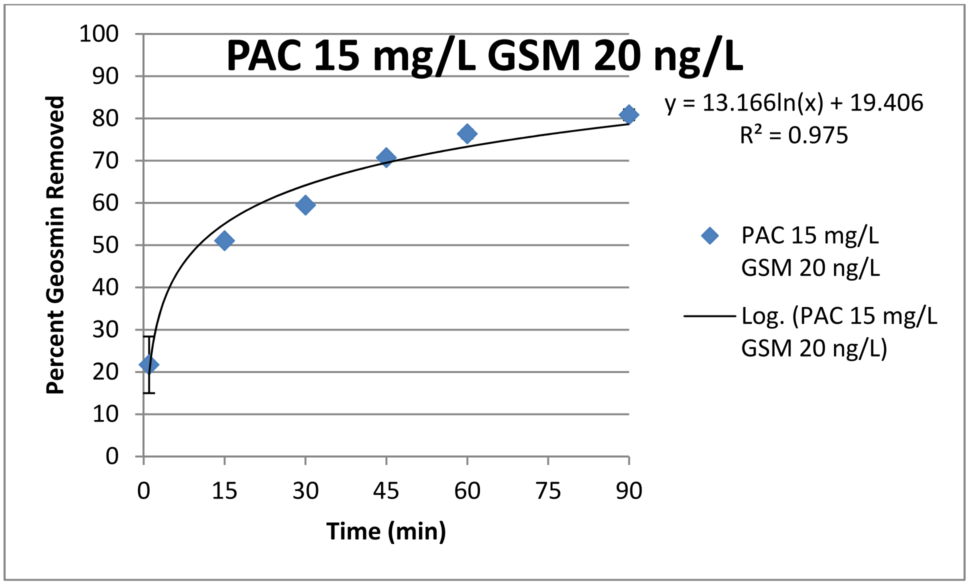


Figure B.29: Percent Removed for Run 6

Table B.71: Concentration Remaining for Run 6

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	14.13	16.61	16.25	15.7	1.3
15	9.78	9.88	9.71	9.8	0.1
30	8.03	8.12	8.17	8.1	0.1
45	6.01	5.82	5.73	5.9	0.1
60	4.89	4.81	4.49	4.7	0.2
90	3.97	3.99	3.53	3.8	0.3

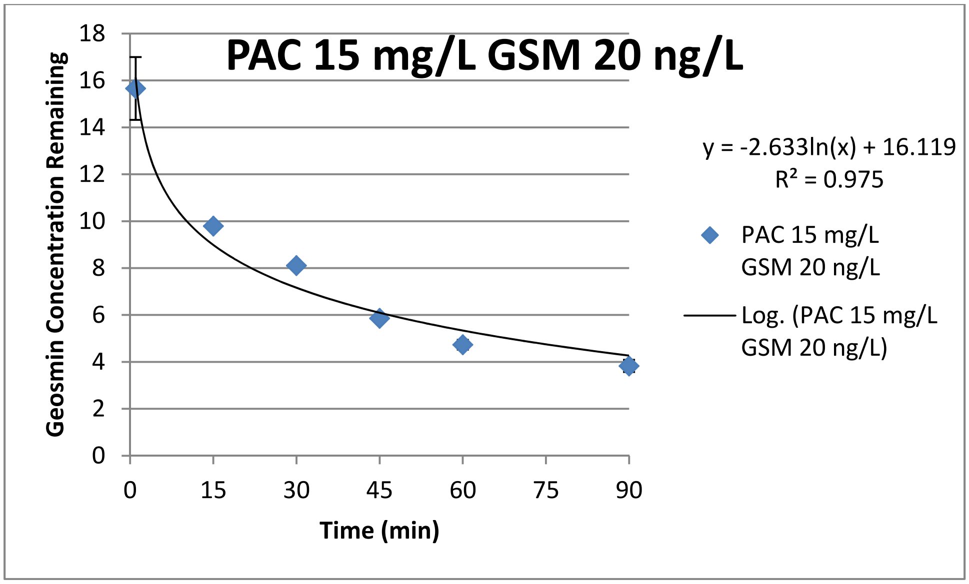


Figure B.30: Concentration Remaining for Run 6

Table B.72: Water Quality for Run 6

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	16	16	15	15.7	°C
pH	7.5	7.6	7.5	7.5	
DO	8.8	9	8.8	8.9	mg/L
Turbidity	2.38	2.47	2.33	2.4	NTU
Conductivity	75	75	74	74.7	µs/cm
TOC	3.37	3.37	3.37	3.37	mg/L

VII. Run 7: PAC 15 mg/L and Geosmin 30 ng/L

Table B.73: Control Values for Replicate 1

Control	Area	Conc.
1	19529	24.24
30	24657	30.61
60	21290	26.43
90	22629	28.09

Table B.74: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	17810	17020	22.11	21.13	21.62	0.69
15	12114	12867	15.04	15.97	15.51	0.66
30	8263	7553	10.26	9.38	9.82	0.62
45	6711	7094	8.33	8.81	8.57	0.34
60	4167	4692	5.17	5.82	5.50	0.46
90	3262	2949	4.05	3.66	3.86	0.27

Table B.75: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	722
5	2183
10	6599
25	21094

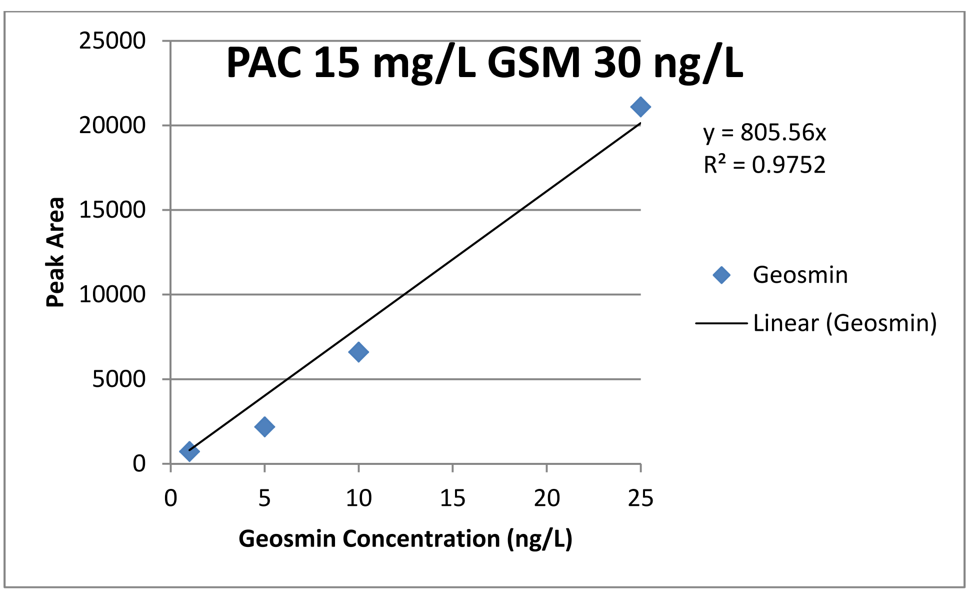


Figure B.31: Standard Curve for Replicate 1

Table B.76: Control Values for Replicate 2

Control	Area	Conc.
1	20413	29.61
30	20979	30.43
60	19444	28.21
90	20276	29.41

Table B.77: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	17951	18112	26.04	26.27	26.16	0.17
15	10767	10350	15.62	15.01	15.32	0.43
30	6543	6247	9.49	9.06	9.28	0.30
45	4653	4476	6.75	6.49	6.62	0.18
60	3541	3539	5.14	5.13	5.14	0.00
90	2309	2611	3.35	3.79	3.57	0.31

Table B.78: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	504
5	4081
10	7253
25	16971

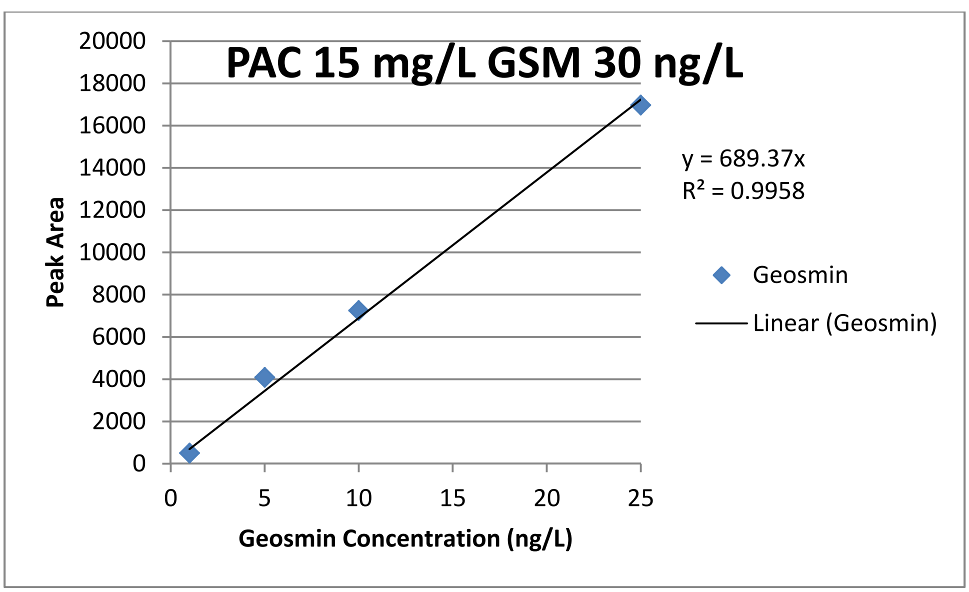


Figure B.32: Standard Curve for Replicate 2

Table B.79: Control Values for Replicate 3

Control	Area	Conc.
1	18326	30.12
30	18367	30.19
60	18834	30.96
90	17445	28.67

Table B.80: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	11575	12194	19.02	20.04	19.53	0.72
15	8405	8080	13.81	13.28	13.55	0.38
30	7671	7480	12.61	12.29	12.45	0.22
45	3864	4394	6.35	7.22	6.79	0.62
60	2871	2816	4.72	4.63	4.67	0.06
90	2504	2183	4.12	3.59	3.85	0.37

Table B.81: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	1105
5	3956
10	6797
25	14723

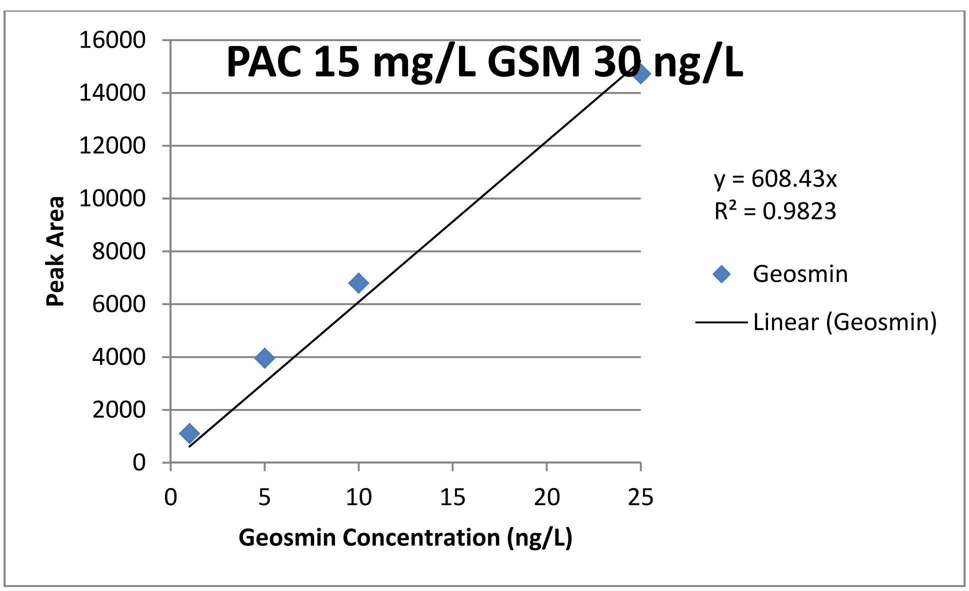


Figure B.33: Standard Curve for Replicate 33

Table B.82: Percent Removed for Run 7

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	28	13	35	25.2	11.3
15	48	49	55	50.7	3.6
30	67	69	58	65.0	5.7
45	71	78	77	75.6	3.6
60	82	83	84	83.0	1.4
90	87	88	87	87.5	0.5

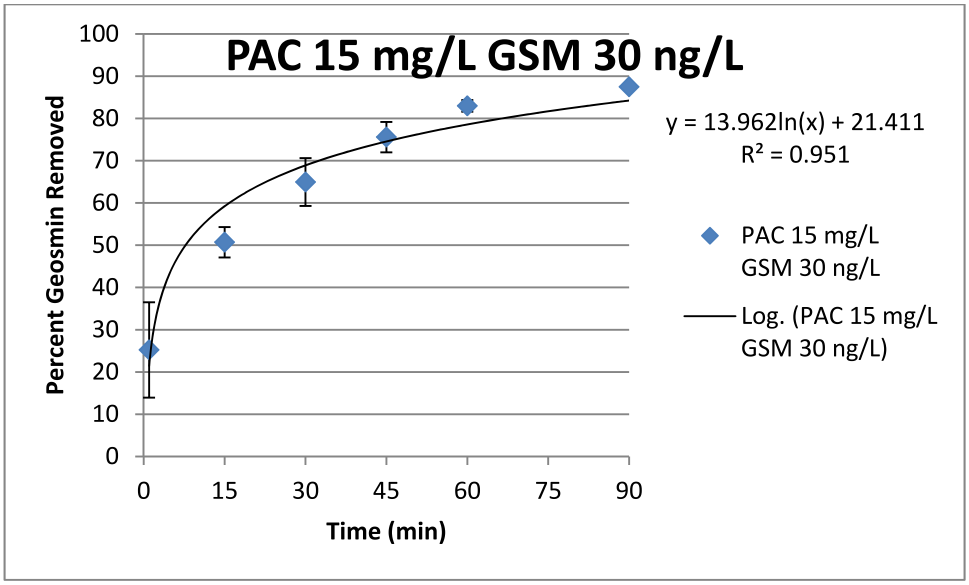


Figure B.34: Percent Removed for Run 7

Table B.83: Concentration Remaining for Run 7

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	21.62	26.16	19.53	22.4	3.4
15	15.51	15.32	13.55	14.8	1.1
30	9.82	9.28	12.45	10.5	1.7
45	8.57	6.62	6.79	7.3	1.1
60	5.50	5.14	4.67	5.1	0.4
90	3.86	3.57	3.85	3.8	0.2

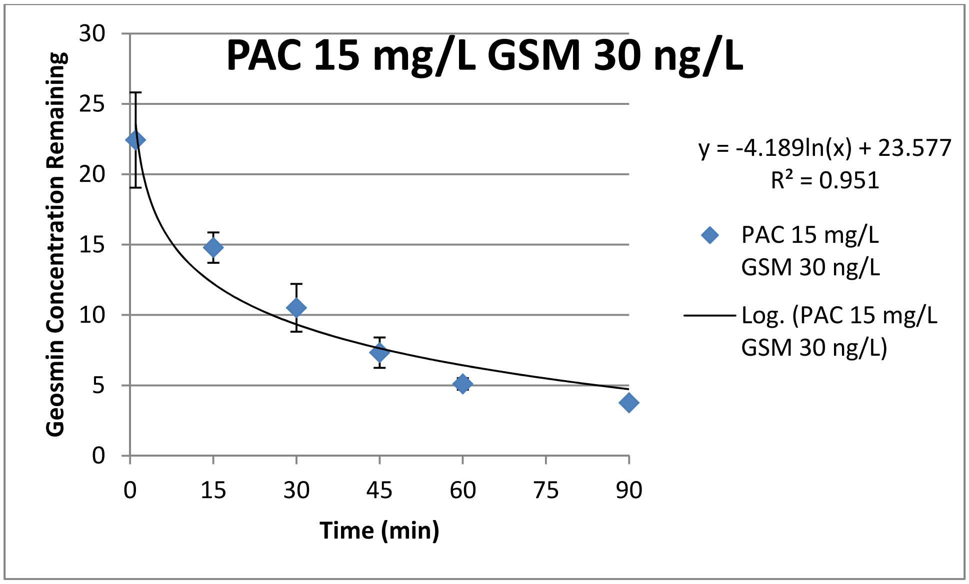


Figure B.35: Concentration Remaining for Run 7

Table B.84: Water Quality for Run 7

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	15	15	15	15	°C
pH	7.3	7.2	7.6	7.4	
DO	9.4	9.3	9.4	9.4	mg/L
Turbidity	2.22	2.25	2.22	2.2	NTU
Conductivity	76	82	78	78.7	µs/cm
TOC	3.78	3.78	3.81	3.79	mg/L

VIII. Run 8: PAC 15 mg/L and Geosmin 40 ng/L

Table B.85: Control Values for Replicate 1

Control	Area	Conc.
1	77867	39.27
30	68973	34.78
60	75133	37.89
120	69851	35.22

Table B.86: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	67660	69714	34.12	35.16	34.64	0.73
15	37153	38214	18.74	19.27	19.00	0.38
30	27338	29193	13.79	14.72	14.25	0.66
45	21463	22720	10.82	11.46	11.14	0.45
60	19517	17406	9.84	8.78	9.31	0.75
90	15051	14030	7.59	7.08	7.33	0.36
120	9569	9999	4.83	5.04	4.93	0.15

Table B.87: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	2378
5	6519
10	20174
25	50101

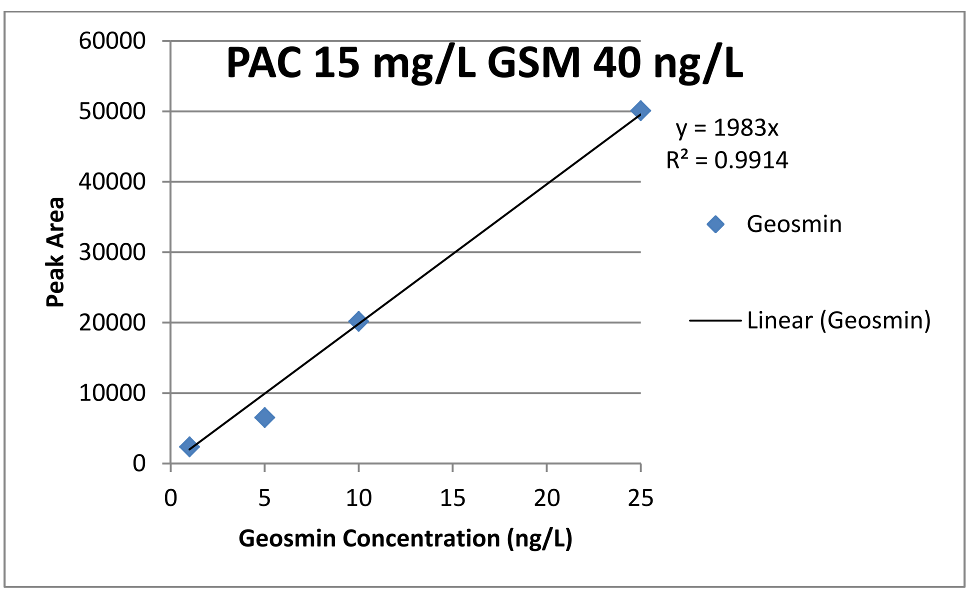


Figure B.36: Standard Curve for Replicate 1

Table B.88: Control Values for Replicate 2

Control	Area	Conc.
1	71340	39.63
30	69540	38.63
60	69522	38.62
120	70690	39.27

Table B.89: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	63056	61632	35.03	34.24	34.63	0.56
15	34478	33181	19.15	18.43	18.79	0.51
30	24070	21344	13.37	11.86	12.61	1.07
45	17394	18676	9.66	10.37	10.02	0.50
60	18193	17339	10.11	9.63	9.87	0.34
90	14996	14101	8.33	7.83	8.08	0.35
120	13064	12679	7.26	7.04	7.15	0.15

Table B.90: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	3065
5	8637
10	18132
25	44973

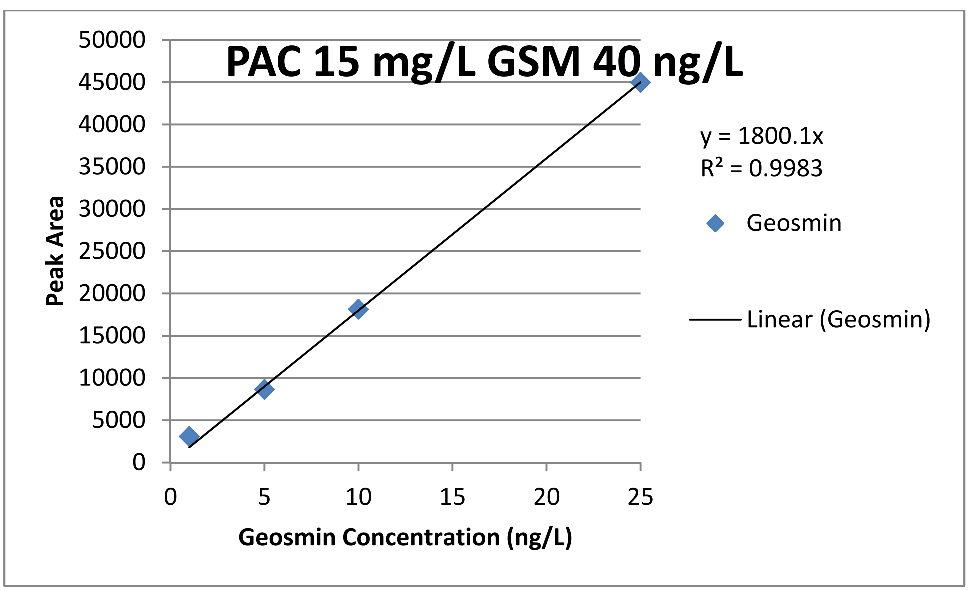


Figure B.37: Standard Curve for Replicate 2

Table B.91: Control Values for Replicate 3

Control	Area	Conc.
1	12980	40.60
30	12201	38.16
60	12451	38.94
120	12776	39.96

Table B.92: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	9189	9180	28.74	28.71	28.72	0.02
15	6463	6247	20.21	19.54	19.88	0.48
30	4510	4606	14.11	14.41	14.26	0.21
45	3206	3379	10.03	10.57	10.30	0.38
60	2792	2856	8.73	8.93	8.83	0.14
90	2074	2182	6.49	6.82	6.66	0.24
120	1749	1871	5.47	5.85	5.66	0.27

Table B.93: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	459
5	1798
10	3412
25	7679

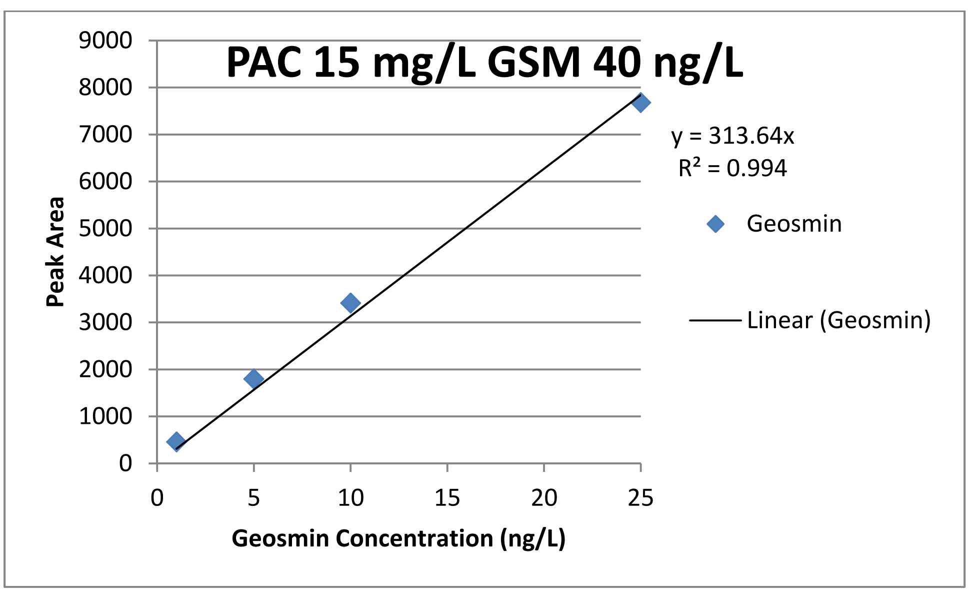


Figure B.38: Standard Curve for Replicate 3

Table B.94: Percent Removed for Run 8

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	11	13	28	17.6	9.2
15	51	53	50	51.5	1.4
30	63	68	64	65.4	2.7
45	71	75	74	73.5	1.9
60	76	75	78	76.5	1.3
90	81	80	83	81.5	1.8
120	87	82	86	85.1	2.7

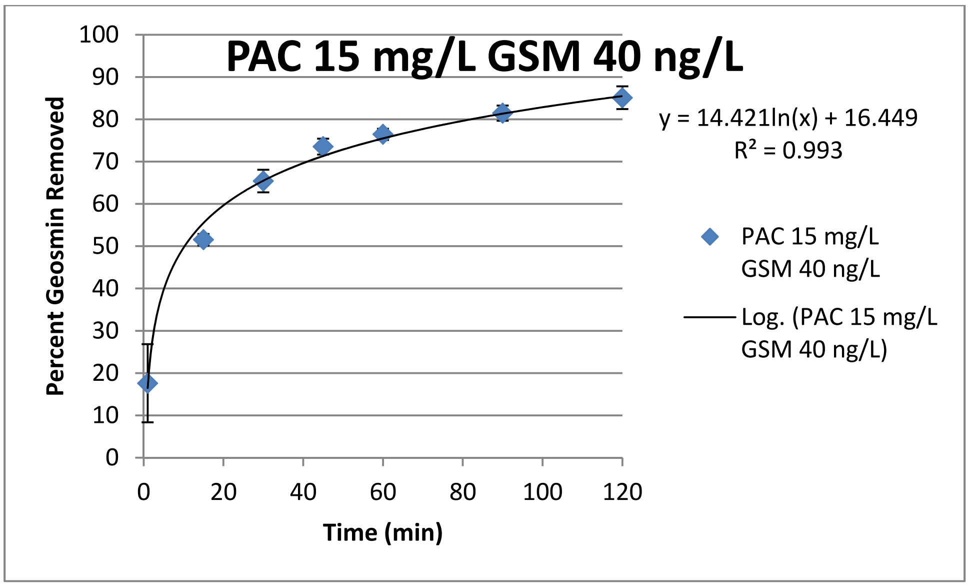


Figure B.39: Percent Removed for Run 8

Table B.95: Concentration Remaining for Run 8

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	34.64	34.63	28.72	32.7	3.4
15	19.00	18.79	19.88	19.2	0.6
30	14.25	12.61	14.26	13.7	0.9
45	11.14	10.02	10.30	10.5	0.6
60	9.31	9.87	8.83	9.3	0.5
90	7.33	8.08	6.66	7.4	0.7
120	4.93	7.15	5.66	5.9	1.1

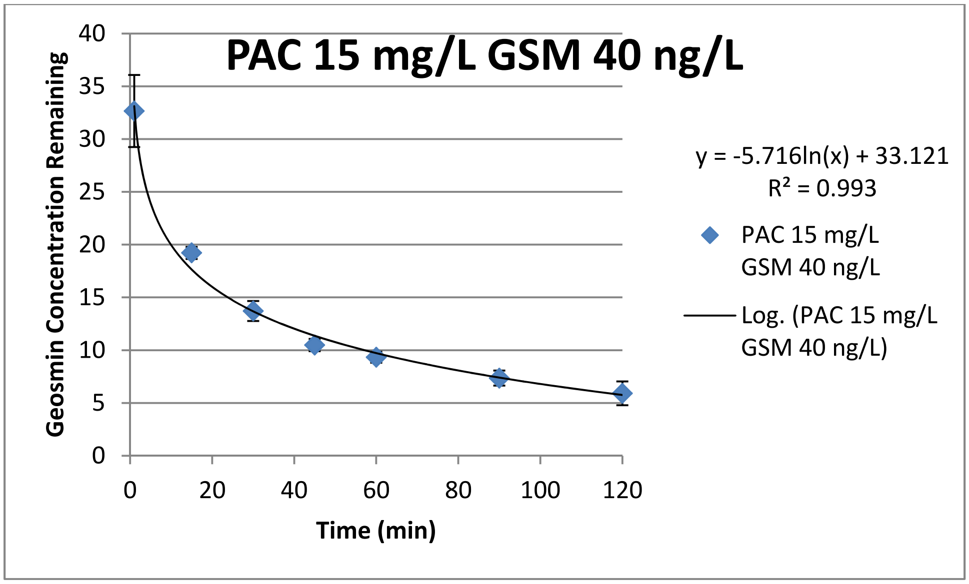


Figure B.40: Concentration Remaining for Run 8

Table B.96: Water Quality for Run 8

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	17	16	15	16	°C
pH	--	--	7.6	7.6	
DO	--	--	9.32	9.3	mg/L
Turbidity	2.36	2.52	2.25	2.4	NTU
Conductivity	--	--	77	77.0	µs/cm
TOC	3.76	3.76	3.9	3.81	mg/L

IX. Run 9: PAC 20 mg/L and Geosmin 30 ng/L

Table B.97: Control Values for Replicate 1

Control	Area	Conc.
1	20206	28.65
30	21196	30.05
60	20345	28.85
90	20900	29.63

Table B.98: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	14483	13840	20.54	19.62	20.08	0.64
15	8325	8678	11.80	12.30	12.05	0.35
30	4747	4395	6.73	6.23	6.48	0.35
45	1417	1545	2.01	2.19	2.10	0.13
60	1190	1438	1.69	2.04	1.86	0.25
90	1132	1135	1.61	1.61	1.61	0.00

Table B.99: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	912
5	4114
10	7947
25	17148

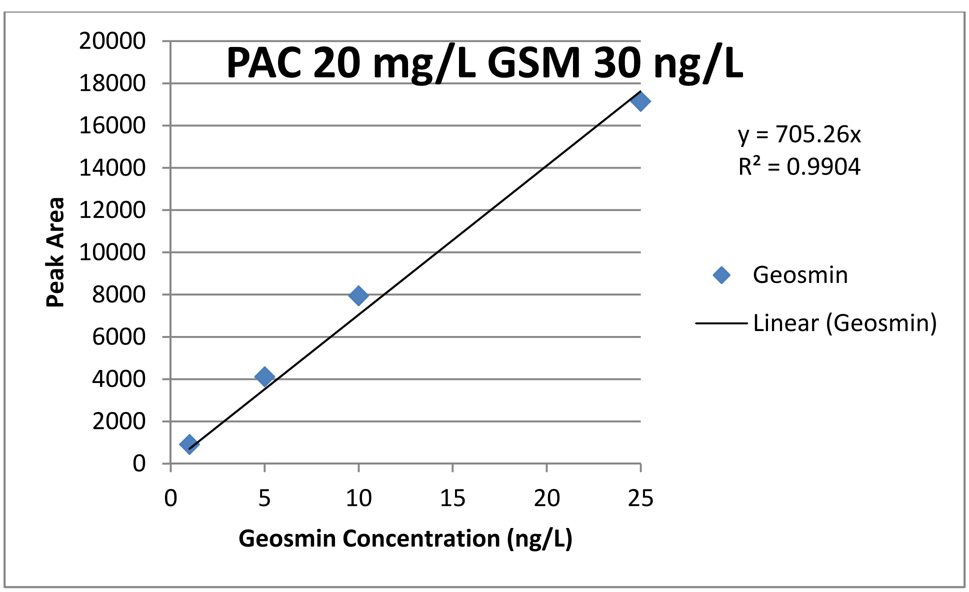


Figure B.41: Standard Curve for Replicate 1

Table B.100: Control Values for Replicate 2

Control	Area	Conc.
1	20497	30.15
30	20468	30.11
60	19619	28.86
90	19919	29.30

Table B.101: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	16776	16410	23.79	23.27	23.53	0.37
15	7881	7631	11.17	10.82	11.00	0.25
30	6063	5903	8.60	8.37	8.48	0.16
45	3926	4193	5.57	5.95	5.76	0.27
60	1747	1913	2.48	2.71	2.59	0.17
90	1157	1298	1.64	1.84	1.74	0.14

Table B.102: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	1628
5	3771
10	7005
25	16799

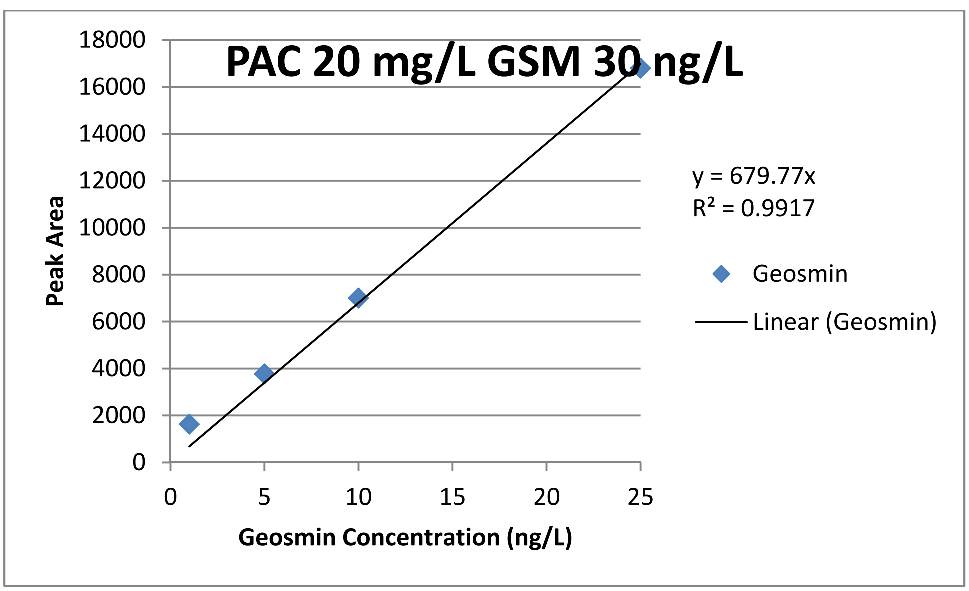


Figure B.42: Standard Curve for Replicate 2

Table B.103: Control Values for Replicate 3

Control	Area	Conc.
1	23367	30.75
30	22502	29.61
60	22775	29.97
90	22245	29.27

Table B.104: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	15598	16064	22.12	22.78	22.45	0.47
15	7247	7616	10.28	10.80	10.54	0.37
30	5585	6117	7.92	8.67	8.30	0.53
45	3785	3987	5.37	5.65	5.51	0.20
60	1541	1746	2.19	2.48	2.33	0.21
90	1158	1310	1.64	1.86	1.75	0.15

Table B.105: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	645
5	3523
10	7117
25	19252

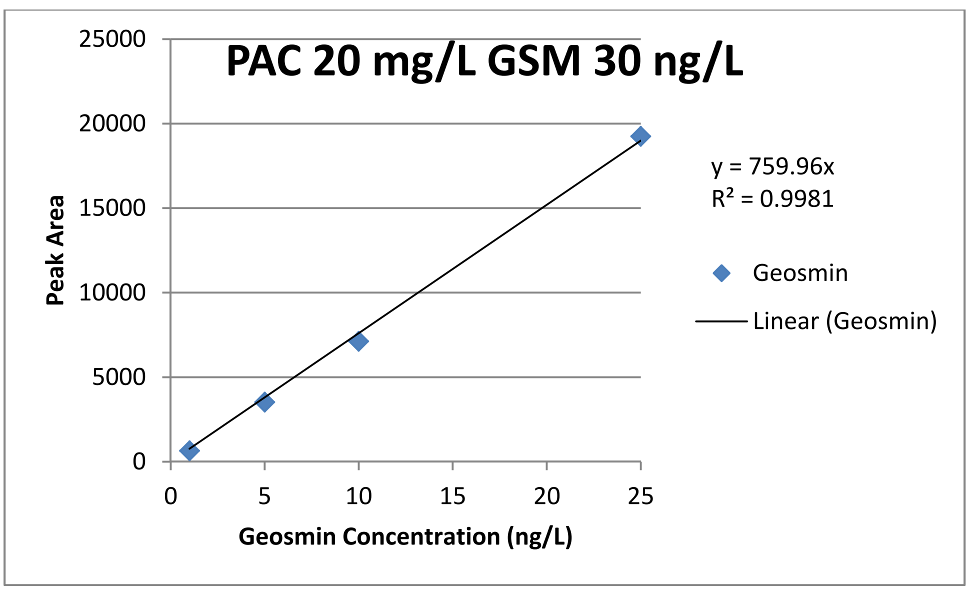


Figure B.43: Geosmin Standard for Replicate 3

Table B.106: Percent Removed for Run 9

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	33	22	25	26.6	5.9
15	60	63	65	62.7	2.6
30	78	72	72	74.2	3.7
45	93	81	82	85.1	6.8
60	94	91	92	92.5	1.2
90	95	94	94	94.3	0.3

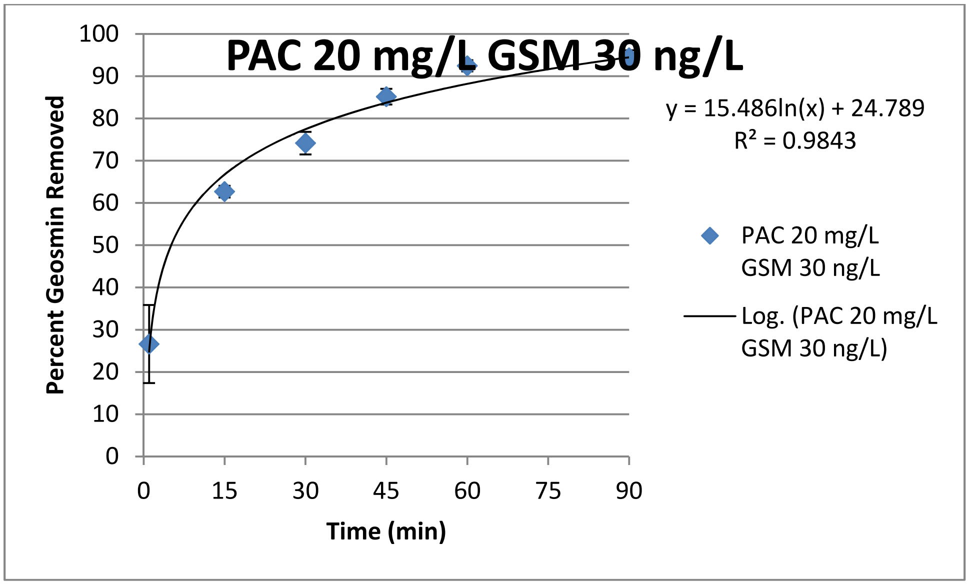


Figure B.44: Percent Removed for Run 9

Table B.107: Concentration Remaining for Run 9

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	20.08	23.53	22.45	22.0	1.8
15	12.05	11.00	10.54	11.2	0.8
30	6.48	8.48	8.30	7.8	1.1
45	2.10	5.76	5.51	4.5	2.0
60	1.86	2.59	2.33	2.3	0.4
90	1.61	1.74	1.75	1.7	0.1

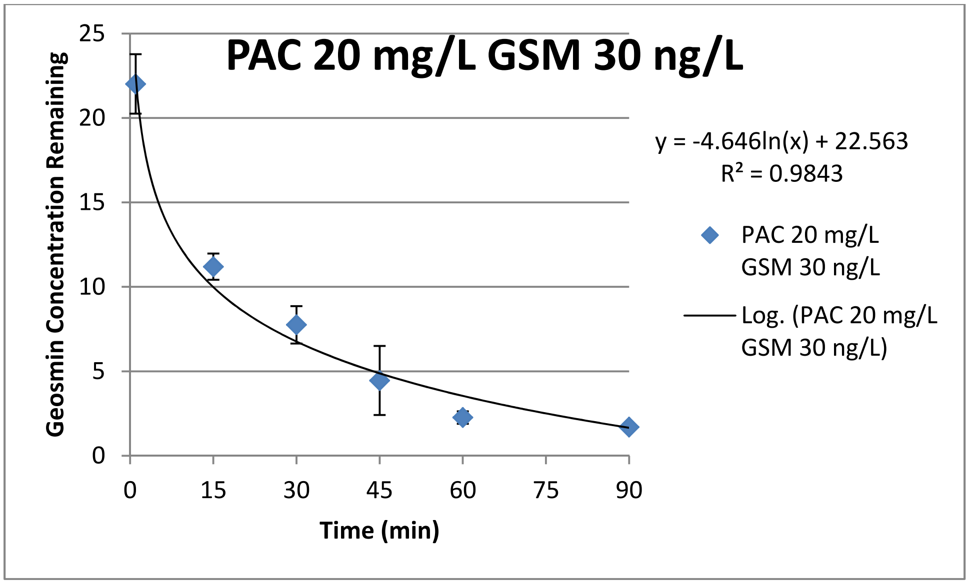


Figure B.45: Concentration Remaining for Run 9

Table B.108: Water Quality for Run 9

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	15	15	16	15.3	°C
pH	7.7	7.4	7.5	7.5	
DO	9.6	9.3	9.3	9.4	mg/L
Turbidity	2.06	2.34	2.28	2.2	NTU
Conductivity	74	74	74	74.0	µs/cm
TOC	3.88	3.74	3.74	3.79	mg/L

X. Run 10: PAC 20 mg/L and Geosmin 40 ng/L

Table B.109: Control Values for Replicate 1

Control	Area	Conc.
1	27197	40.14
30	26305	38.82
60	27128	40.03
90	26711	39.42

Table B.110: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	19922	20325	29.40	29.99	29.70	0.42
15	9631	9613	14.21	14.19	14.20	0.02
30	6620	7037	9.77	10.38	10.08	0.44
45	4678	4856	6.90	7.17	7.03	0.19
60	4086	3825	6.03	5.64	5.84	0.27
90	2176	2106	3.21	3.11	3.16	0.07

Table B.111: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	751
5	4299
10	7852
25	16325

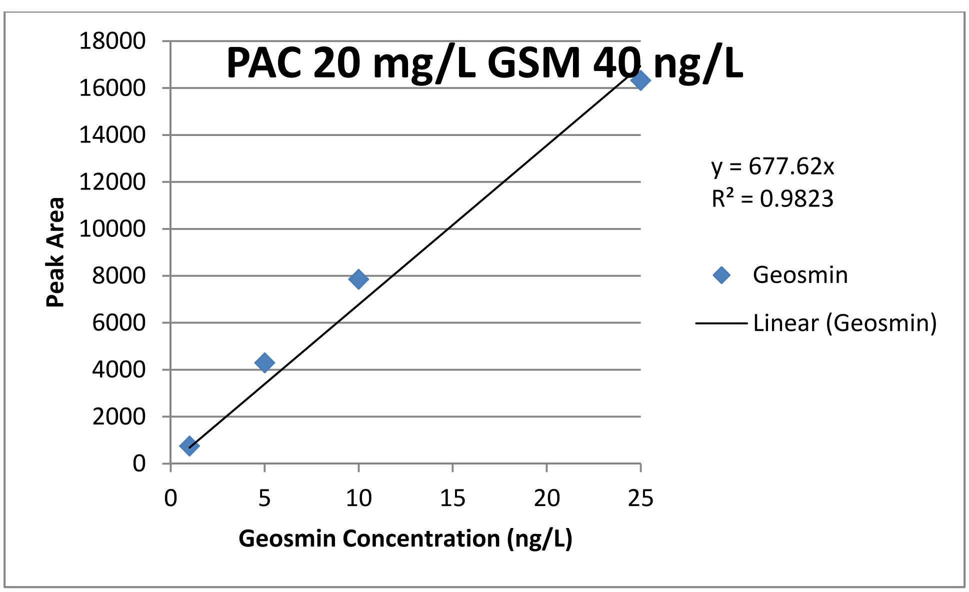


Figure B.46: Standard Curve for Replicate 1

Table B.112: Control Values for Replicate 2

Control	Area	Conc.
1	27660	40.82
30	--	--
60	26272	38.77
90	26425	39.00

Table B.113: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	22620	23124	33.38	34.13	33.75	0.53
15	13855	13008	20.45	19.20	19.82	0.88
30	8549	9240	12.62	13.64	13.13	0.72
45	5171	5853	7.63	8.64	8.13	0.71
60	3408	3808	5.03	5.62	5.32	0.42
90	2034	1987	3.00	2.93	2.97	0.05

Table B.114: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	751
5	4299
10	7852
25	16325

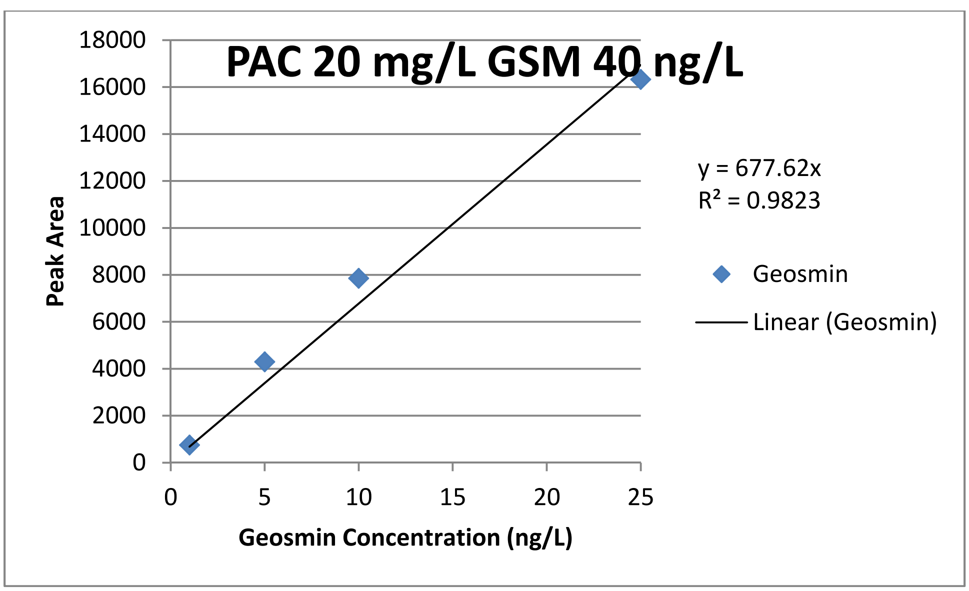


Figure B.47: Standard Curve for Replicate 2

Table B.115: Control Values for Replicate 3

Control	Area	Conc.
1	27581	39.11
30	27745	39.34
60	24427	34.64
90	27787	39.40

Table B.116: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	24166	23513	34.27	33.34	33.80	0.65
15	9965	9415	14.13	13.35	13.74	0.55
30	7084	6731	10.04	9.54	9.79	0.35
45	4391	4172	6.23	5.92	6.07	0.22
60	3501	3266	4.96	4.63	4.80	0.24
90	2457	2389	3.48	3.39	3.44	0.07

Table B.117: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	912
5	4114
10	7947
25	17148

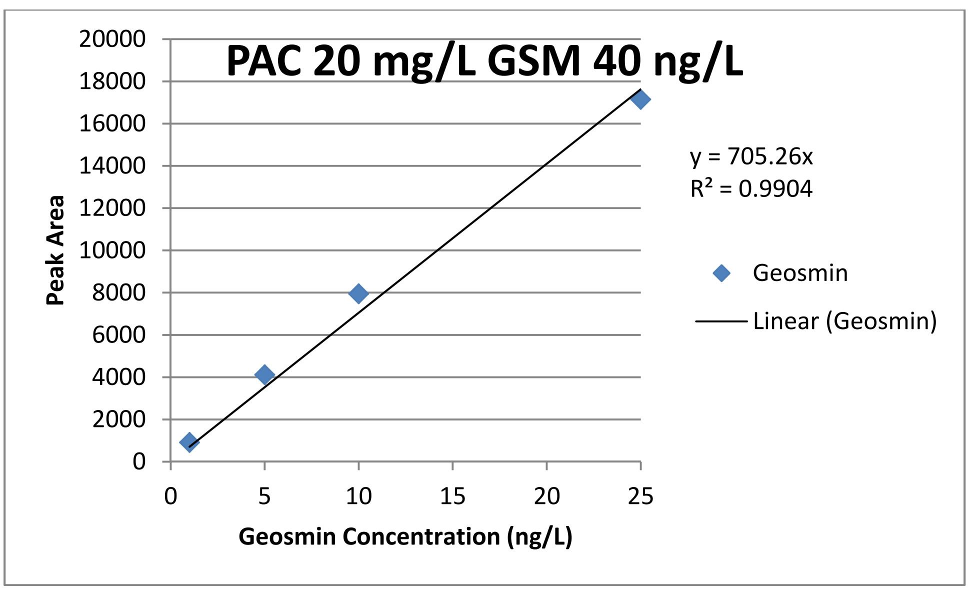


Figure B.48: Standard Curve for Replicate 3

Table B.118: Percent Removed for Run 10

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	26	16	15	19.0	5.9
15	65	50	66	60.2	8.5
30	75	67	76	72.5	4.6
45	82	80	85	82.3	2.6
60	85	87	88	86.7	1.3
90	92	93	91	92.0	0.6

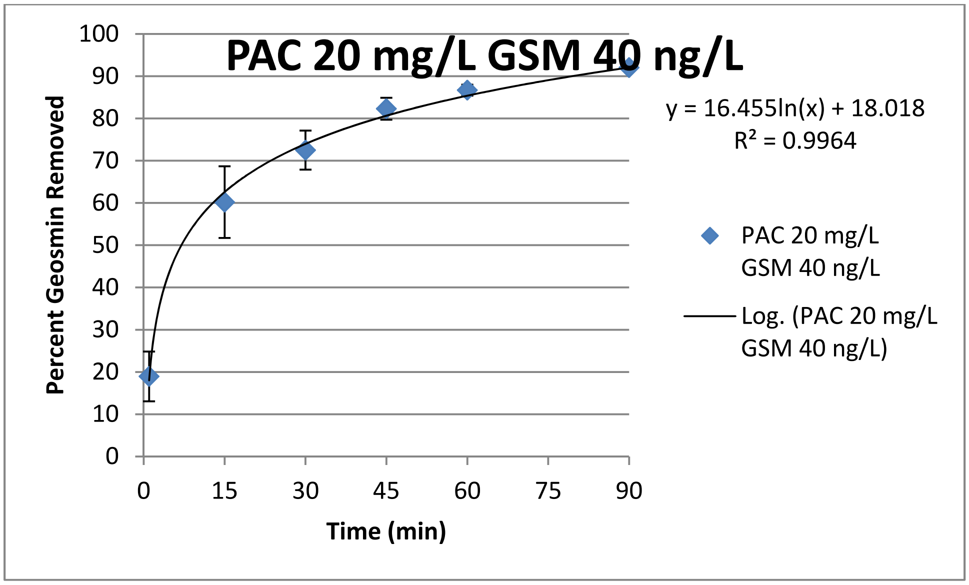


Figure B.49: Percent Removed for Run 10

Table B.119: Concentration Remaining for Run 10

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	29.70	33.75	33.80	32.4	2.4
15	14.20	19.82	13.74	15.9	3.4
30	10.08	13.13	9.79	11.0	1.8
45	7.03	8.13	6.07	7.1	1.0
60	5.84	5.32	4.80	5.3	0.5
90	3.16	2.97	3.44	3.2	0.2

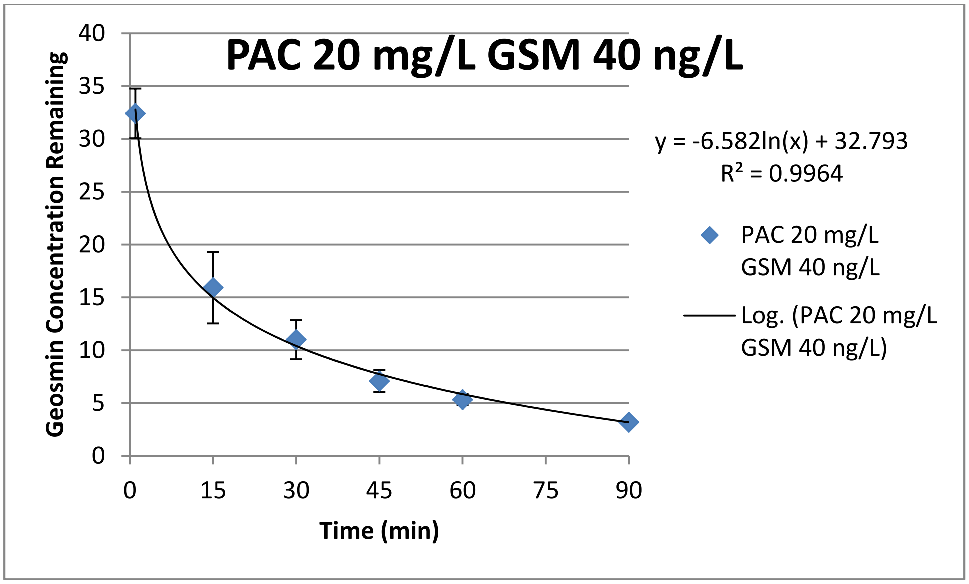


Figure B.50: Concentration Remaining for Run 10

Table B.120: Water Quality for Run 10

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	16	15	16	15.7	°C
pH	7.7	7.7	7.6	7.7	
DO	9.5	9.5	9.4	9.5	mg/L
Turbidity	1.85	2.35	2.14	2.1	NTU
Conductivity	75	75	75	75.0	µs/cm
TOC	3.81	3.88	3.88	3.86	mg/L

XI. Run 11: PAC 20 mg/L and Geosmin 50 ng/L

Table B.121: Control Values for Replicate 1

Control	Area	Conc.
1	95560	46.88
30	100195	49.16
60	93575	45.91
120	86127	42.26

Table B.122: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	69521	69950	34.11	34.32	34.21	0.15
15	30020	30378	14.73	14.90	14.82	0.12
30	24002	23923	11.78	11.74	11.76	0.03
45	15221	14844	7.47	7.28	7.38	0.13
60	12827	12412	6.29	6.09	6.19	0.14
90	11764	11882	5.77	5.83	5.80	0.04
120	9439	9230	4.63	4.53	4.58	0.07

Table B.123: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	2213
5	10009
10	22005
25	50336

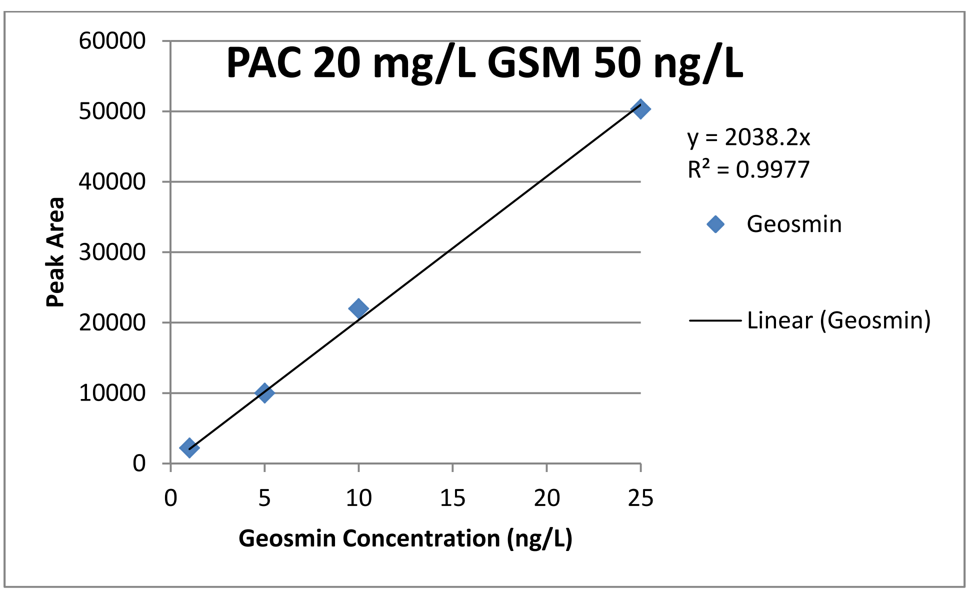


Figure B.51: Standard Curve for Replicate 1

Table B.124: Control Values for Replicate 2

Control	Area	Conc.
1	101168	49.64
30	94371	46.30
60	97720	47.94
120	96257	47.23

Table B.125: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	60711	60967	29.79	29.91	29.85	0.09
15	32309	31334	15.85	15.37	15.61	0.34
30	22664	21858	11.12	10.72	10.92	0.28
45	19329	18585	9.48	9.12	9.30	0.26
60	14221	14189	6.98	6.96	6.97	0.01
90	12386	12501	6.08	6.13	6.11	0.04
120	10802	10738	5.30	5.27	5.28	0.02

Table B.126: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	2213
5	10009
10	22005
25	50336

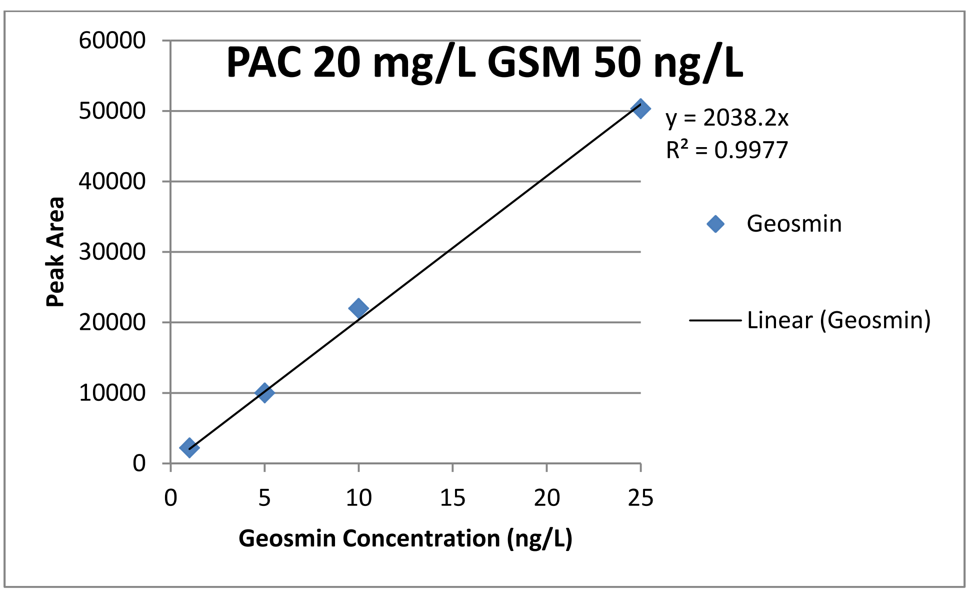


Figure B.52: Standard Curve for Replicate 2

Table B.127: Control Values for Replicate 3

Control	Area	Conc.
1	15555	48.65
30	15814	49.46
60	15058	47.09
120	15694	49.08

Table B.128: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	13326	13064	41.68	40.86	41.27	0.58
15	5364	5214	16.78	16.31	16.54	0.33
30	3685	3482	11.52	10.89	11.21	0.45
45	2784	2755	8.71	8.62	8.66	0.06
60	2297	2225	7.18	6.96	7.07	0.16
90	1832	1793	5.73	5.61	5.67	0.09
120	1401	1423	4.38	4.45	4.42	0.05

Table B.129: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	459
5	1798
10	3412
25	7679

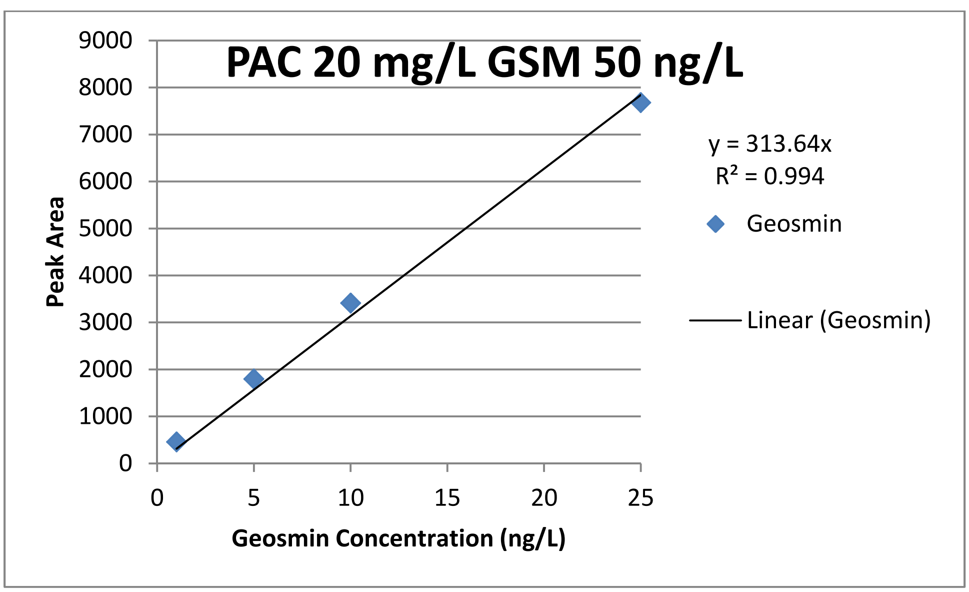


Figure B.53: Standard Curve for Replicate 2

Table B.130: Percent Removed for Run 11

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	29	38	17	28.0	10.2
15	69	67	67	67.8	1.2
30	76	77	78	76.8	1.1
45	85	81	83	82.6	2.0
60	87	85	86	86.1	0.8
90	88	87	89	88.0	0.7
120	90	89	91	90.2	1.1

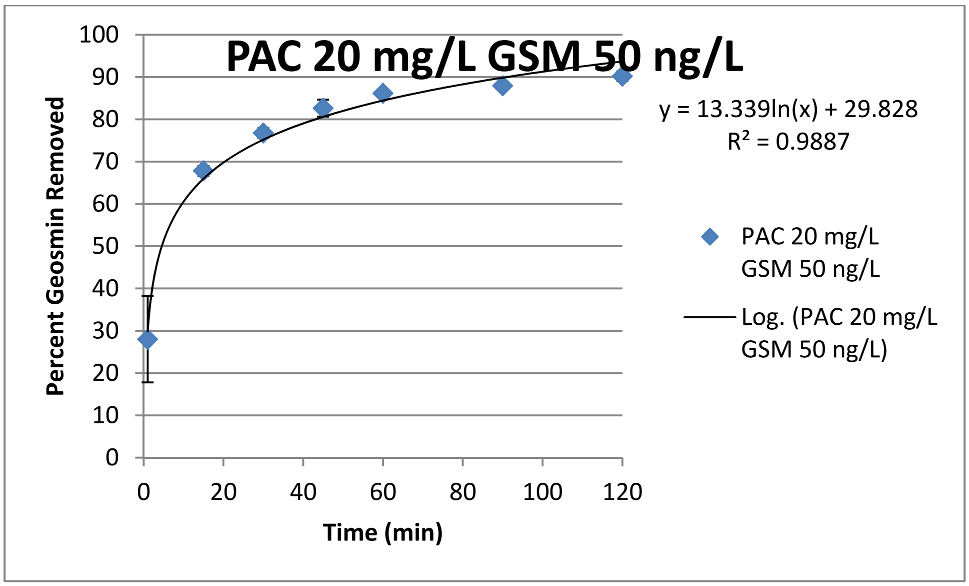


Figure 54: Percent Removed for Run 11

Table B.131: Concentration Remaining for Run 11

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	34.21	29.85	41.27	35.1	5.8
15	14.82	15.61	16.54	15.7	0.9
30	11.76	10.92	11.21	11.3	0.4
45	7.38	9.30	8.66	8.4	1.0
60	6.19	6.97	7.07	6.7	0.5
90	5.80	6.11	5.67	5.9	0.2
120	4.58	5.28	4.42	4.8	0.5

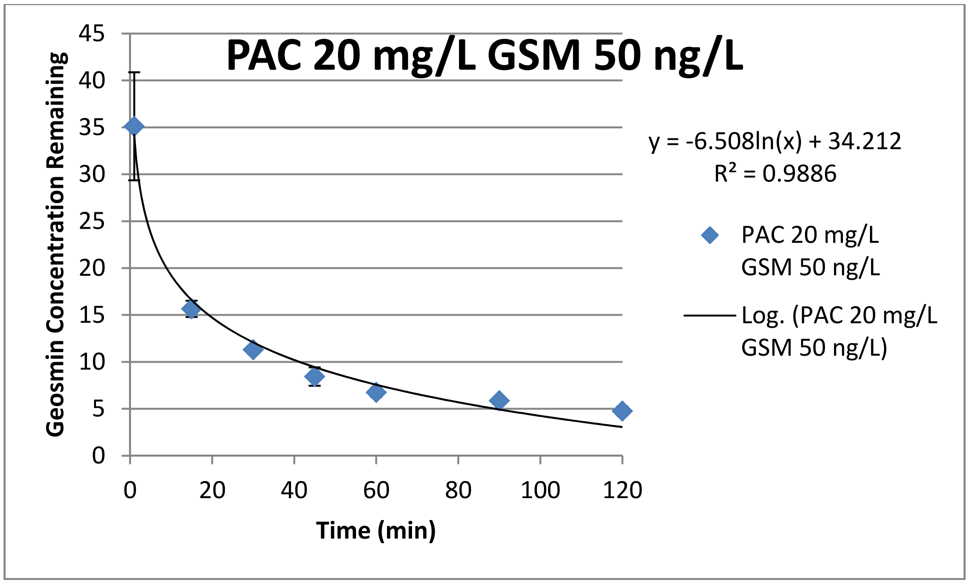


Figure B.55: Concentration Remaining for Run 11

Table B.132: Water Quality for Run 11

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	16	16	16	16	°C
pH	--	--	7.7	7.7	
DO	--	--	9.28	9.3	mg/L
Turbidity	2.45	2.49	2.3	2.4	NTU
Conductivity	--	--	79	79.0	µs/cm
TOC	3.76	3.76	3.90	3.81	mg/L

XII. Run 12: PAC 30 mg/L and Geosmin 40 ng/L

Table B.133: Control Values for Replicate 1

Control	Area	Conc.
1	27645	39.20
30	27932	39.61
60	27387	38.83
90	28164	39.93

Table B.134: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	19363	18569	27.46	26.33	26.89	0.80
15	6978	7678	9.89	10.89	10.39	0.70
30	2825	2762	4.01	3.92	3.96	0.06
45	1755	1733	2.49	2.46	2.47	0.02
60	1583	1520	2.24	2.16	2.20	0.06
90	520	622	0.74	0.88	0.81	0.10

Table B.135: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	912
5	4114
10	7947
25	17148

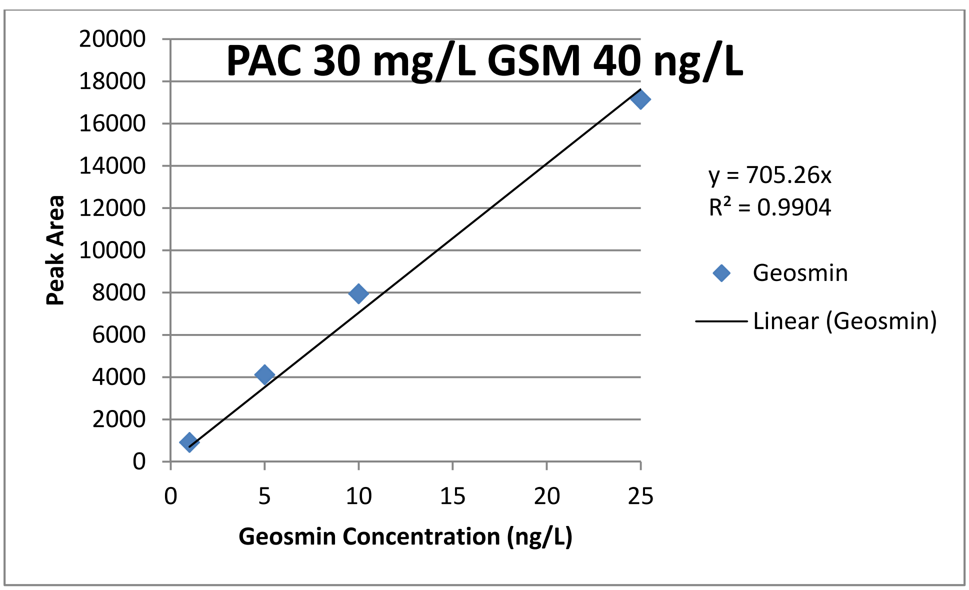


Figure B.56: Standard Curve for Replicate 1

Table B.136: Control Values for Replicate 2

Control	Area	Conc.
1	27463	40.40
30	27180	39.98
60	26257	38.63
90	25647	37.73

Table B.137: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	18459	18272	27.15	26.88	27.02	0.19
15	7014	6441	10.32	9.48	9.90	0.60
30	2371	2295	3.49	3.38	3.43	0.08
45	1633	1918	2.40	2.82	2.61	0.30
60	1462	1596	2.15	2.35	2.25	0.14
90	656	659	0.97	0.97	0.97	0.00

Table B.138: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	1628
5	3771
10	7005
25	16799

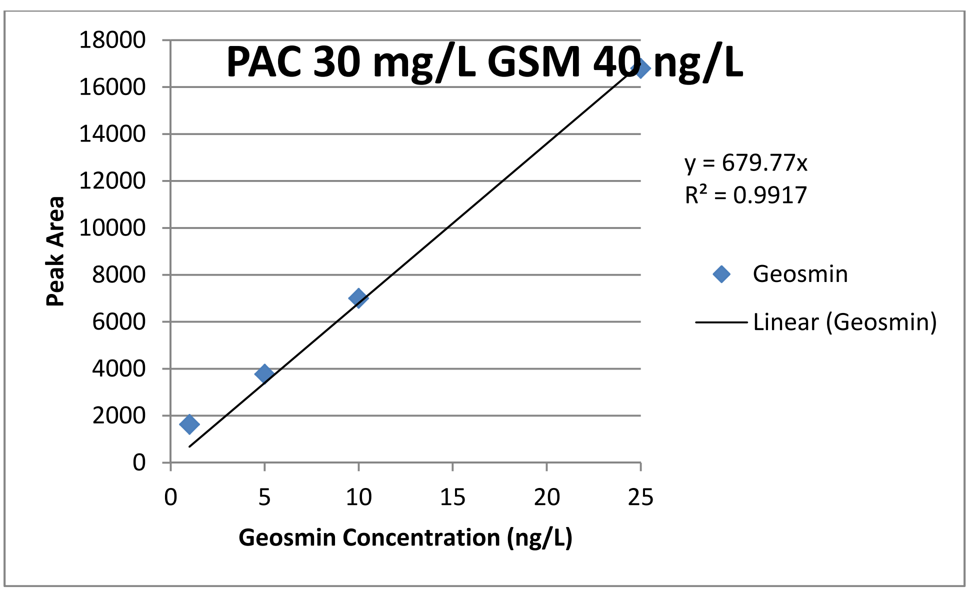


Figure B.57: Standard Curve for Replicate 2

Table B.139: Control Values for Replicate 3

Control	Area	Conc.
1	30492	40.12
30	29781	39.19
60	29222	38.45
90	29912	39.36

Table B.140: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	18946	19804	24.93	26.06	25.49	0.80
15	6750	7643	8.88	10.06	9.47	0.83
30	3235	3103	4.26	4.08	4.17	0.12
45	2205	2046	2.90	2.69	2.80	0.15
60	1440	1573	1.89	2.07	1.98	0.12
90	750	871	0.99	1.15	1.07	0.11

Table B.141: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	645
5	3523
10	7117
25	19252

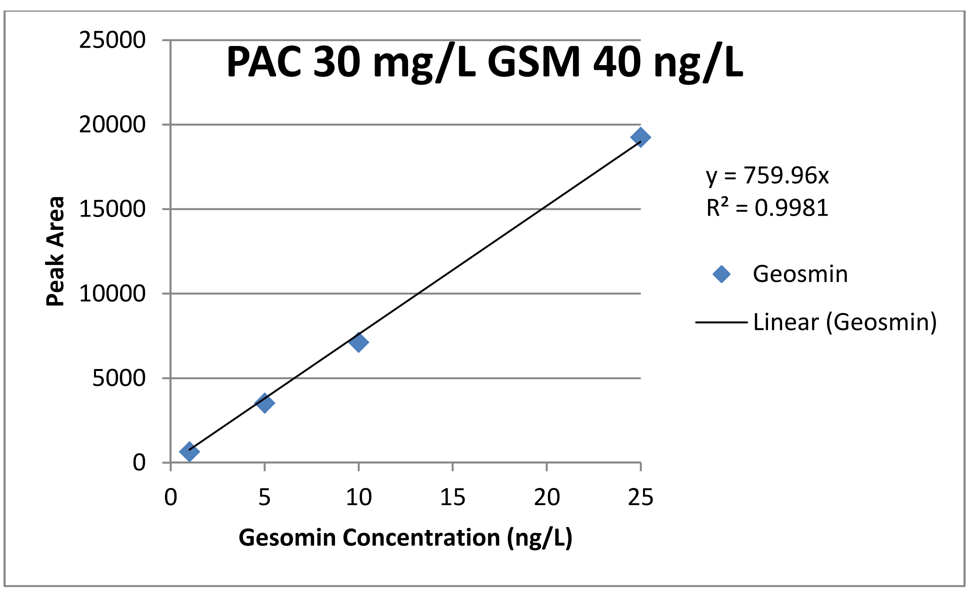


Figure B.58: Standard Curve for Replicate 3

Table B.142: Percent Removed for Run 12

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	33	32	36	33.8	2.1
15	74	75	76	75.2	1.2
30	90	91	90	90.4	1.0
45	94	93	93	93.4	0.4
60	95	94	95	94.6	0.4
90	98	98	97	97.6	0.3

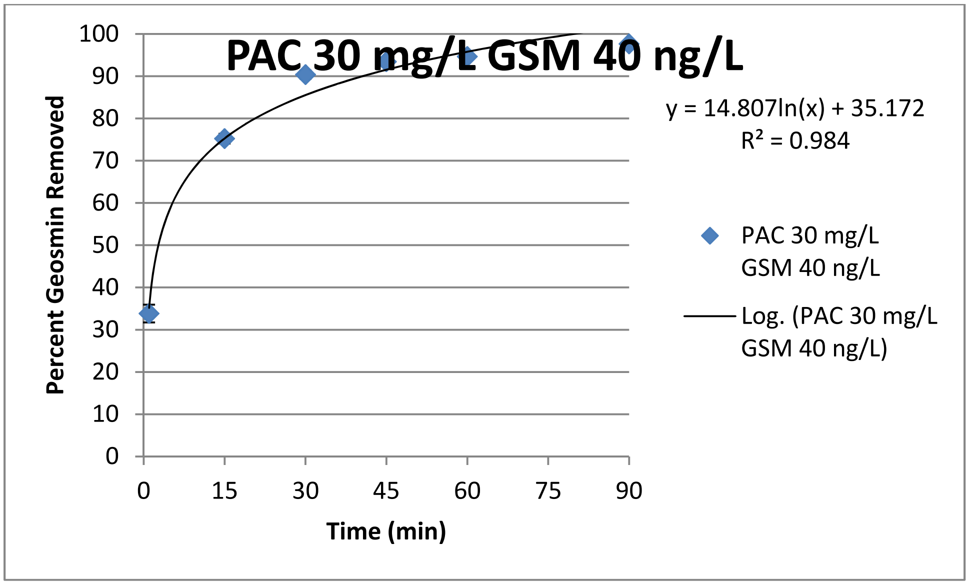


Figure B.59: Percent Removed for Run 12

Table B.143: Concentration Remaining

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	26.89	27.02	25.49	26.5	0.8
15	10.39	9.90	9.47	9.9	0.5
30	3.96	3.43	4.17	3.9	0.4
45	2.47	2.61	2.80	2.6	0.2
60	2.20	2.25	1.98	2.1	0.1
90	0.81	0.97	1.07	0.9	0.1

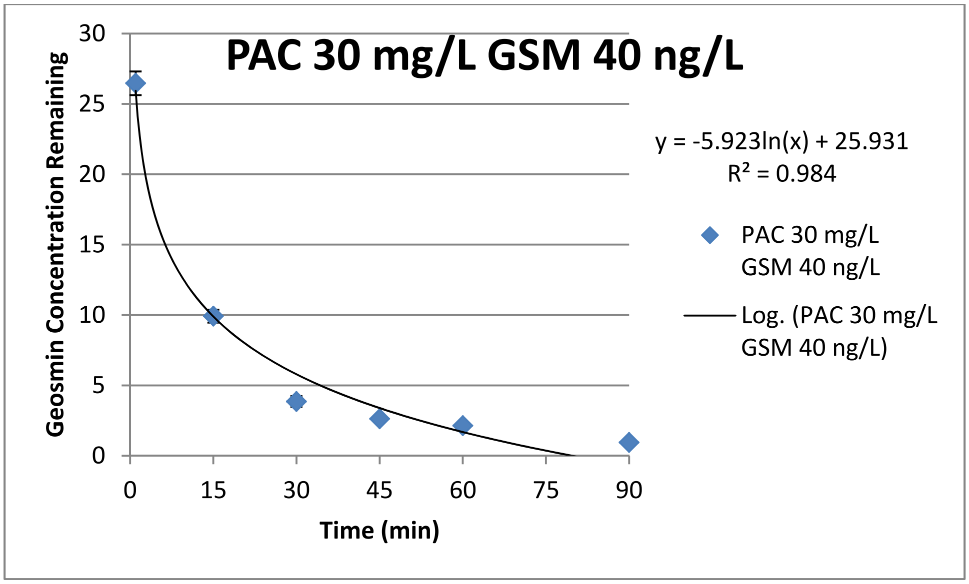


Figure B.60: Concentration Remaining for PAC 30 mg/L and Geosmin 40 ng/L

Table B.144: Water Quality for Run 12

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	15	15	16	15.3	° C
pH	7.7	7.5	7.5	7.6	
DO	9.5	9.2	9.3	9.3	mg/L
Turbidity	1.85	2.21	2.17	2.1	NTU
Conductivity	75	74	75	74.7	µs/cm
TOC	3.88	3.74	3.74	3.79	mg/L

XIII. Run 13: PAC 30 mg/L and Geosmin 50 ng/L

Table B.145: Control Values for Replicate 1

Control	Area	Conc.
1	33567	49.54
30	26121	38.55
60	33490	49.42
90	33415	49.31

Table B.146: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	20260	20965	29.90	30.94	30.42	0.74
15	7208	7628	10.64	11.26	10.95	0.44
30	4720	4189	6.97	6.18	6.57	0.55
45	3128	2820	4.62	4.16	4.39	0.32
60	2543	2560	3.75	3.78	3.77	0.02
90	1861	1470	2.75	2.17	2.46	0.41

Table B.147: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	751
5	4299
10	7852
25	16325

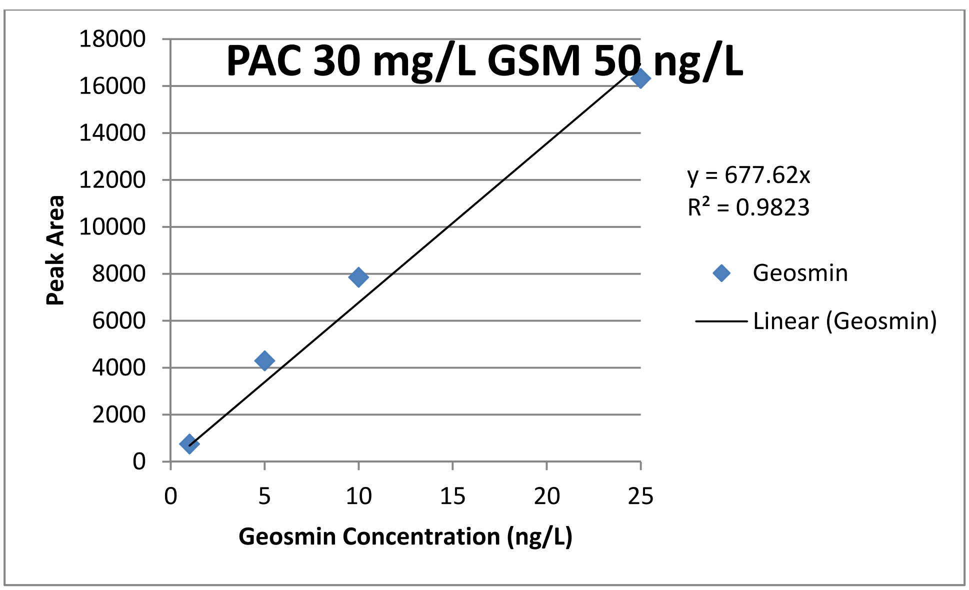


Figure B.61: Standard Curve for Replicate 1

Table B.148: Control Values for Replicate 2

Control	Area	Conc.
1	20630	30.44
30	33847	49.95
60	33260	49.08
90	33790	49.87

Table B.149: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	21875	22030	32.28	32.51	32.40	0.16
15	6090	6502	8.99	9.60	9.29	0.43
30	4839	4402	7.14	6.50	6.82	0.46
45	3328	3007	4.91	4.44	4.67	0.33
60	2132	2147	3.15	3.17	3.16	0.02
90	1954	1894	2.88	2.80	2.84	0.06

Table B.150: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	751
5	4299
10	7852
25	16325

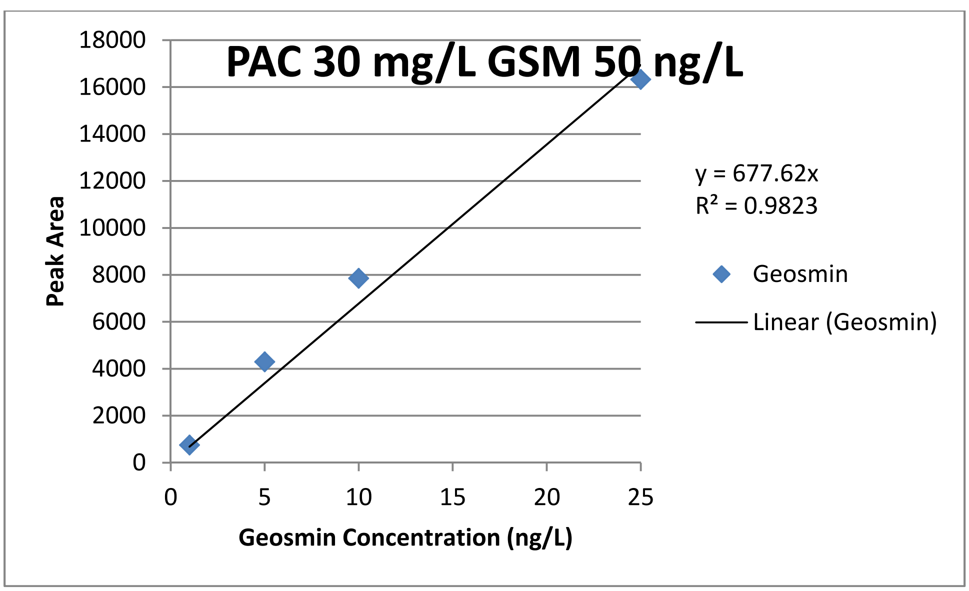


Figure B.62: Standard Curve for Replicate 62

Table B.151: Control Values for Replicate 3

Control	Area	Conc.
1	35151	49.84
30	35800	50.76
60	35014	49.65
90	23777	33.71

Table B.152: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	22270	22108	31.58	31.35	31.46	0.16
15	5861	5872	8.31	8.33	8.32	0.01
30	4069	3676	5.77	5.21	5.49	0.39
45	3370	2948	4.78	4.18	4.48	0.42
60	2287	2458	3.24	3.49	3.36	0.17
90	1886	1688	2.67	2.39	2.53	0.20

Table B.153: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	912
5	4114
10	7947
25	17148

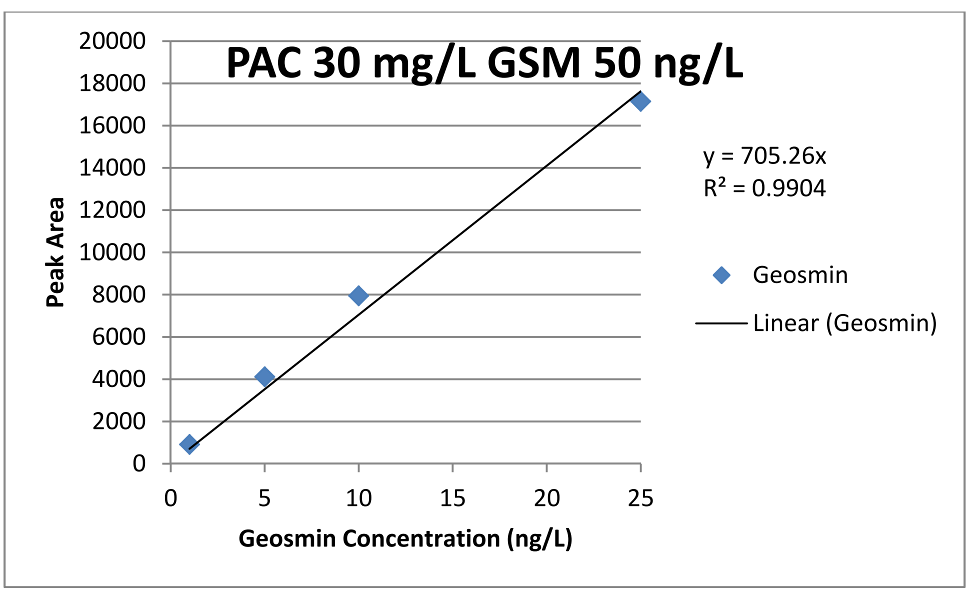


Figure B.63: Standard Curve for Replicate 3

Table B.154: Percent Removed for Run 13

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	39	35	37	37.1	2.0
15	78	81	83	81.0	2.7
30	87	86	89	87.4	1.4
45	91	91	91	91.0	0.3
60	92	94	93	93.1	0.6
90	95	94	95	94.8	0.4

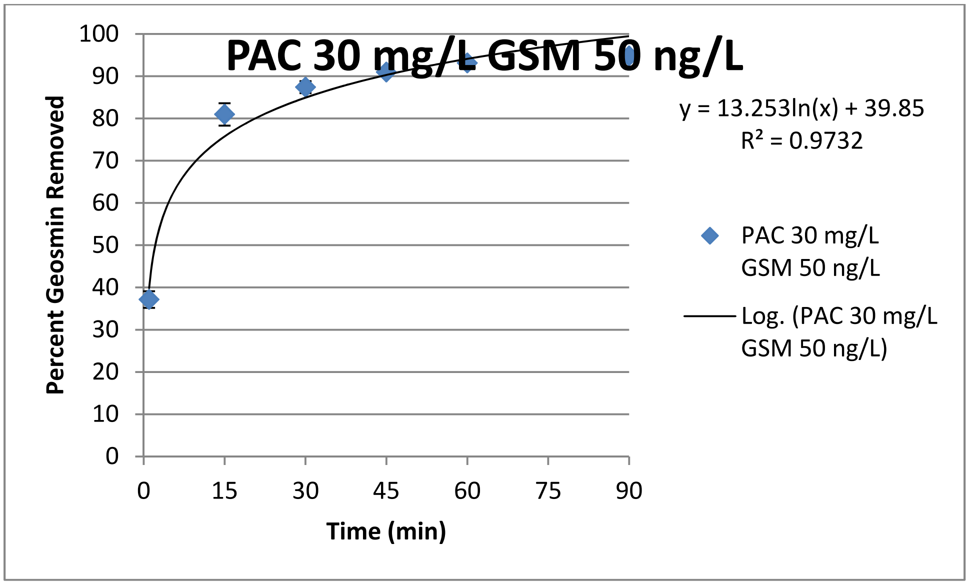


Figure B.64: Percent Removed for Run 13

Table B.155: Concentration Remaining for Run 13

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	30.42	32.40	31.46	31.4	1.0
15	10.95	9.29	8.32	9.5	1.3
30	6.57	6.82	5.49	6.3	0.7
45	4.39	4.67	4.48	4.5	0.1
60	3.77	3.16	3.36	3.4	0.3
90	2.46	2.84	2.53	2.6	0.2

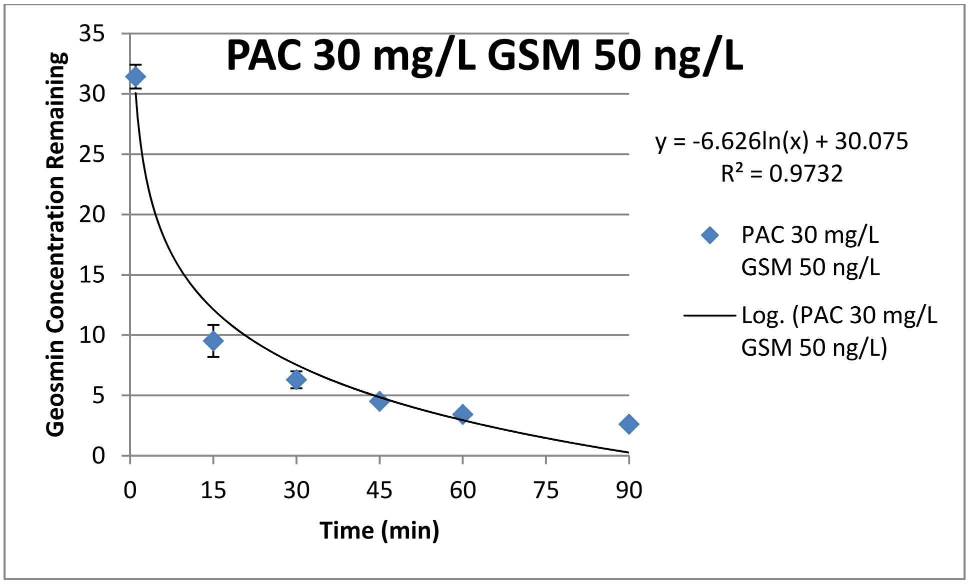


Figure B.65: Concentration Remaining for Run 13

Table B.156: Water Quality for Run 13

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	16	15	15	15.3	°C
pH	7.6	7.6	7.7	7.6	
DO	9.4	9.6	9.5	9.5	mg/L
Turbidity	1.92	2.14	2.05	2.0	NTU
Conductivity	76	74	74	74.7	µs/cm
TOC	3.81	3.88	3.88	3.86	mg/L

XIV. Extra Run: PAC 12.5 mg/L and Geosmin 30 ng/L

Table B.157: Control Values for Replicate 1

Control	Area	Conc.
1	64195	27.29
30	67622	28.75
60	65444	27.82
120	60538	25.74

Table B.158: Peak Areas and Concentrations for Replicate 1

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	52739	51624	22.42	21.95	22.19	0.34
15	36691	35714	15.60	15.18	15.39	0.29
30	30138	29630	12.81	12.60	12.71	0.15
45	21838	20174	9.28	8.58	8.93	0.50
60	19104	18085	8.12	7.69	7.91	0.31
90	13499	15093	5.74	6.42	6.08	0.48
120	14387	13145	6.12	5.59	5.85	0.37

Table B.159: Standard Curve Peak Areas for Replicate 1

Standard	Area
1	3344
5	16369
10	27106
25	56403

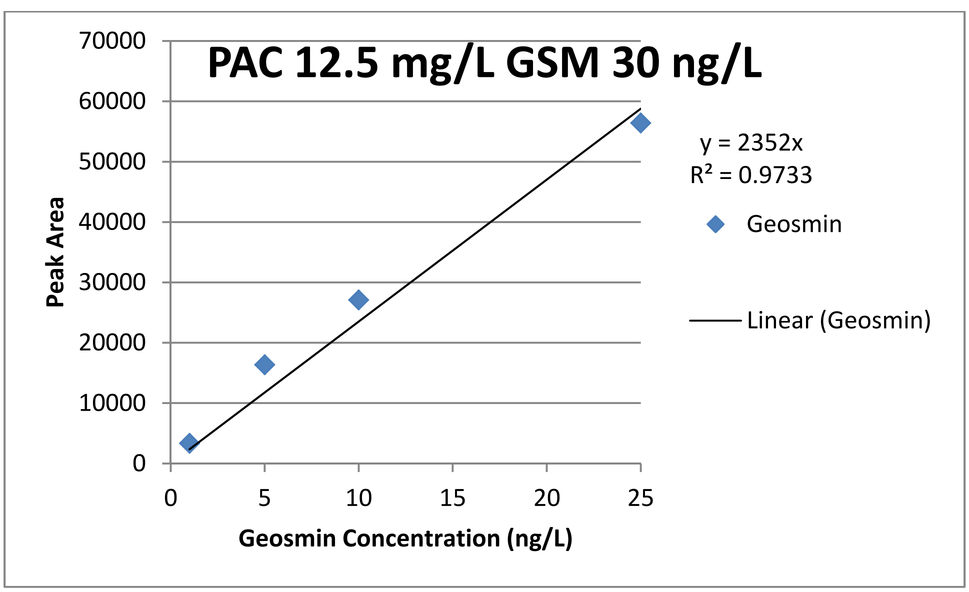


Figure B.66: Standard Curve for Replicate 1

Table B.160: Control Values for Replicate 2

Control	Area	Conc.
1	64196	29.22
30	65821	29.96
60	63727	29.01
120	61515	28.00

Table B.161: Peak Areas and Concentrations for Replicate 2

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	50551	50222	23.01	22.86	22.94	0.11
15	31054	31751	14.14	14.45	14.30	0.22
30	21176	25813	9.64	11.75	10.70	1.49
45	17284	19080	7.87	8.69	8.28	0.58
60	13612	18499	6.20	8.42	7.31	1.57
90	12642	12817	5.75	5.83	5.79	0.06
120	10834	10955	4.93	4.99	4.96	0.04

Table B.162: Standard Curve Peak Areas for Replicate 2

Standard	Area
1	3267
5	14282
10	20696
25	54722

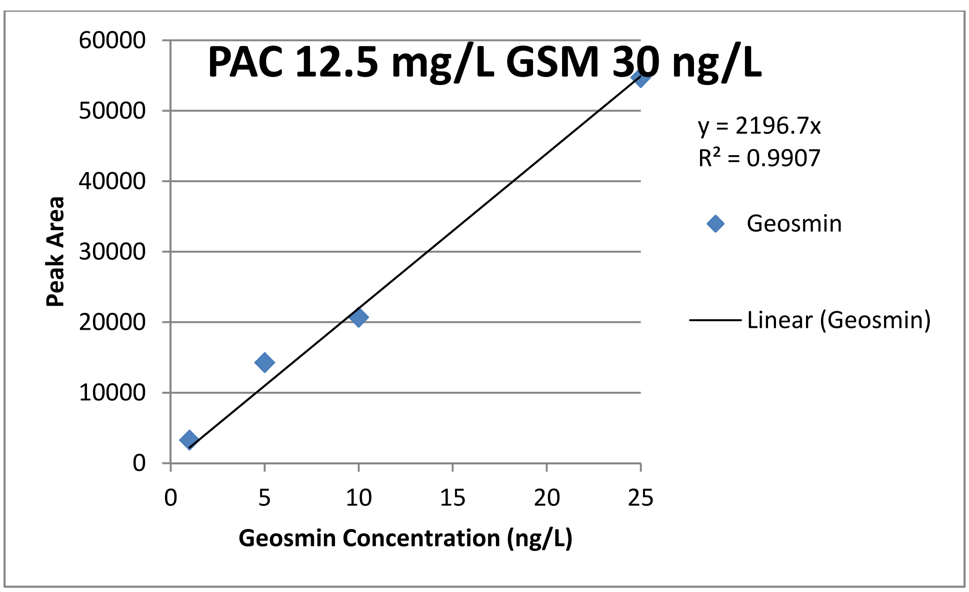


Figure B.67: Standard Curve for Replicate 2

Table B.163: Control Values for Replicate 3

Control	Area	Conc.
1	8806	27.54
30	9476	29.64
60	7383	23.09
120	9121	28.53

Table B.164: Peak Areas and Concentrations for Replicate 3

Samples	Area 1	Area 2	Conc. 1	Conc. 2	Avg.	Std. Dev.
1	7275	7360	22.75	23.02	22.89	0.19
15	4454	4433	13.93	13.86	13.90	0.05
30	3056	3117	9.56	9.75	9.65	0.13
45	2674	2726	8.36	8.53	8.44	0.11
60	1678	1744	5.25	5.45	5.35	0.15
90	1663	1633	5.20	5.11	5.15	0.07
120	1648	1609	5.15	5.03	5.09	0.09

Table B.165: Standard Curve Peak Areas for Replicate 3

Standard	Area
1	517
5	1897
10	3067
25	7978

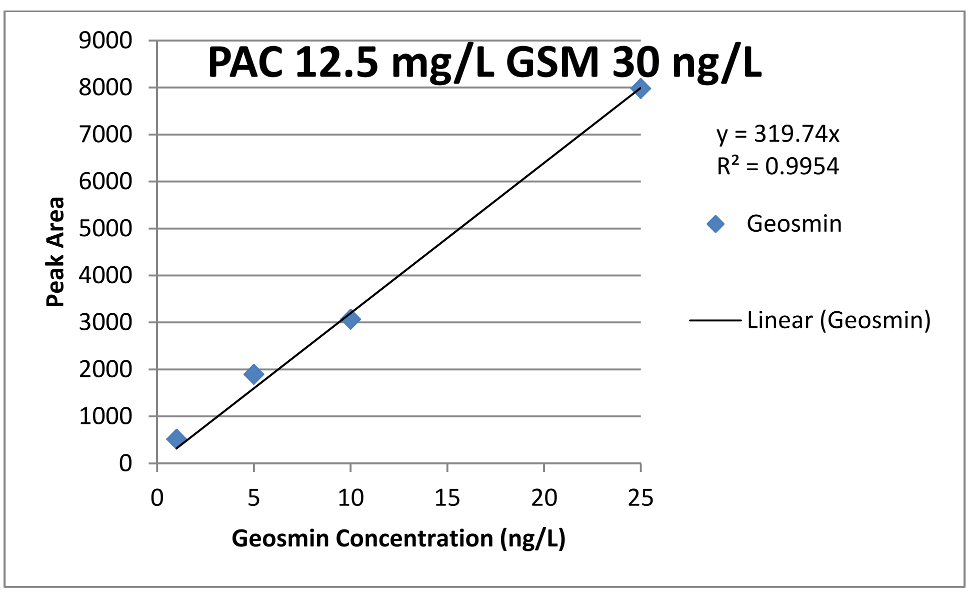


Figure B.68: Standard Curve for Replicate 68

Table B.166: Percent Removed Extra Run

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	23	24	24	23.6	0.1
15	47	52	54	51.0	3.6
30	56	64	68	62.8	6.0
45	69	72	72	71.2	1.7
60	73	76	82	76.8	4.8
90	79	81	83	80.8	1.9
120	80	83	83	82.1	2.0

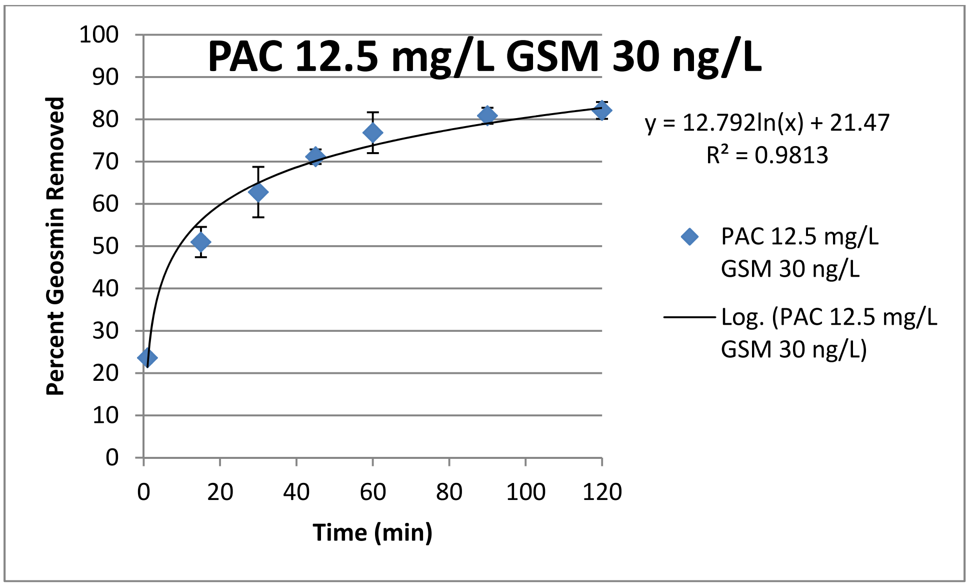


Figure B.69: Percent Removed for Extra Run

Table B.167: Concentration Remaining for Extra Run

Time	Replicate 1	Replicate 2	Replicate 3	Avg.	Std. Dev.
1	22.19	22.94	22.89	22.7	0.4
15	15.39	14.30	13.90	14.5	0.8
30	12.71	10.70	9.65	11.0	1.6
45	8.93	8.28	8.44	8.6	0.3
60	7.91	7.31	5.35	6.9	1.3
90	6.08	5.79	5.15	5.7	0.5
120	5.85	4.96	5.09	5.3	0.5

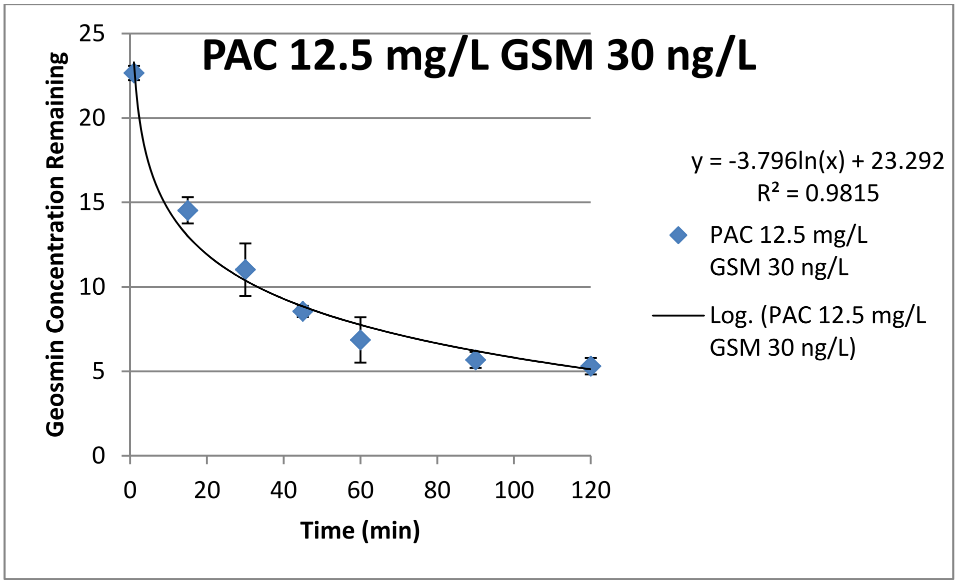


Figure B.70: Concentration Remaining for Extra Run

Table B.168: Water Quality for Extra Run

Water Quality Analysis					
	Replicate 1	Replicate 2	Replicate 3	Avg.	
Temp	17	17	16	17	°C
pH	7.7	7.8	7.6	7.7	
DO	9.2	8.9	9.54	9.2	mg/L
Turbidity	3.78	2.62	2.32	2.9	NTU
Conductivity	88	81.5	78	82.5	µs/cm
TOC	3.85	3.85	3.82	3.84	mg/L

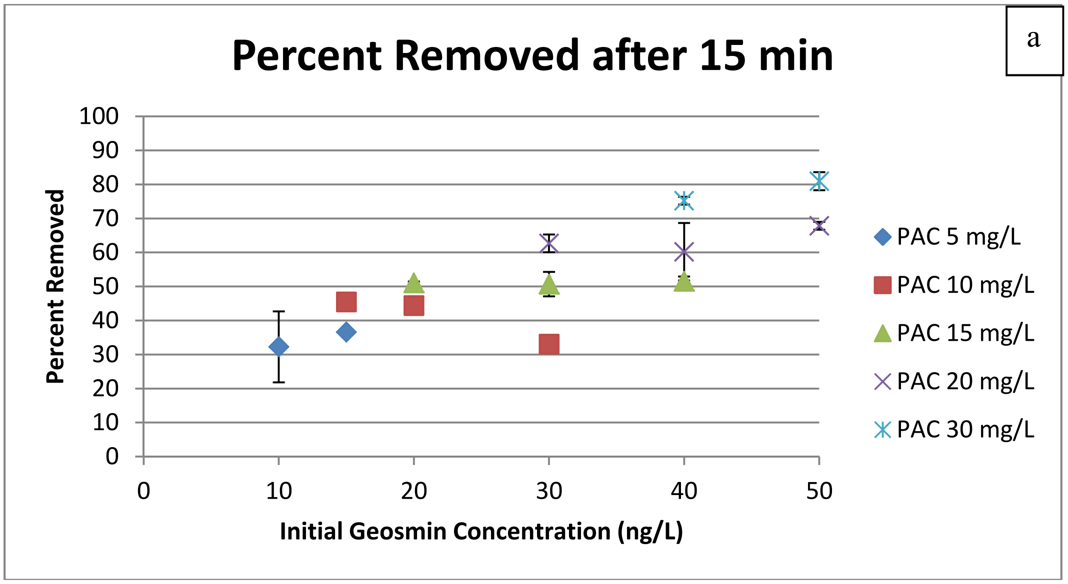
APPENDIX B: COMPARISON OF ALL THE VALUES MEASURED IN THE LABORATORY AND PREDICTED BY THE MODEL

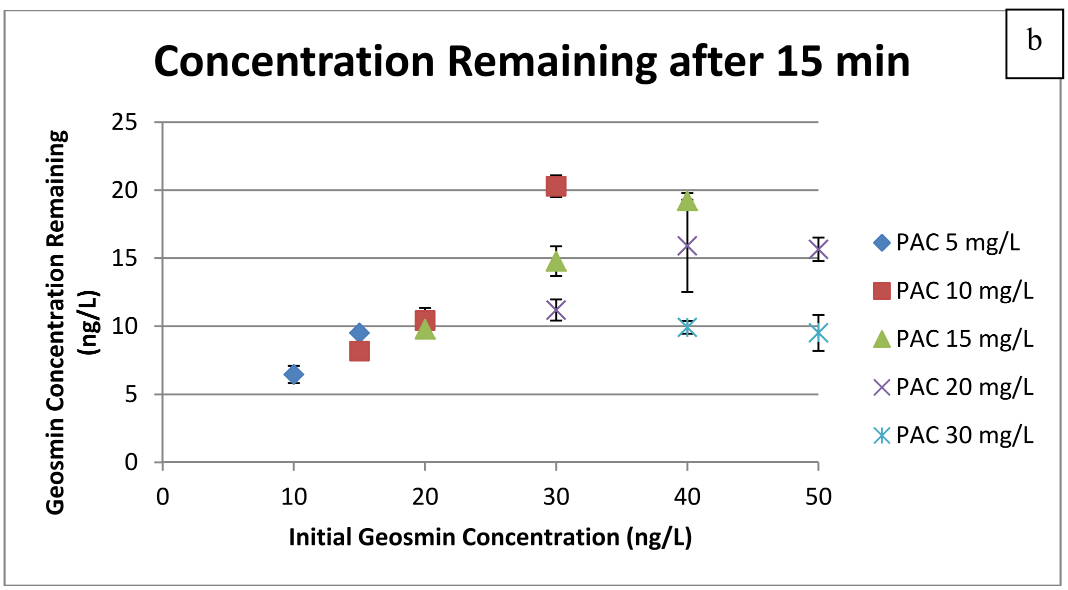
Table C.1: Comparison of Measured and Predicted Concentration Geosmin Remaining

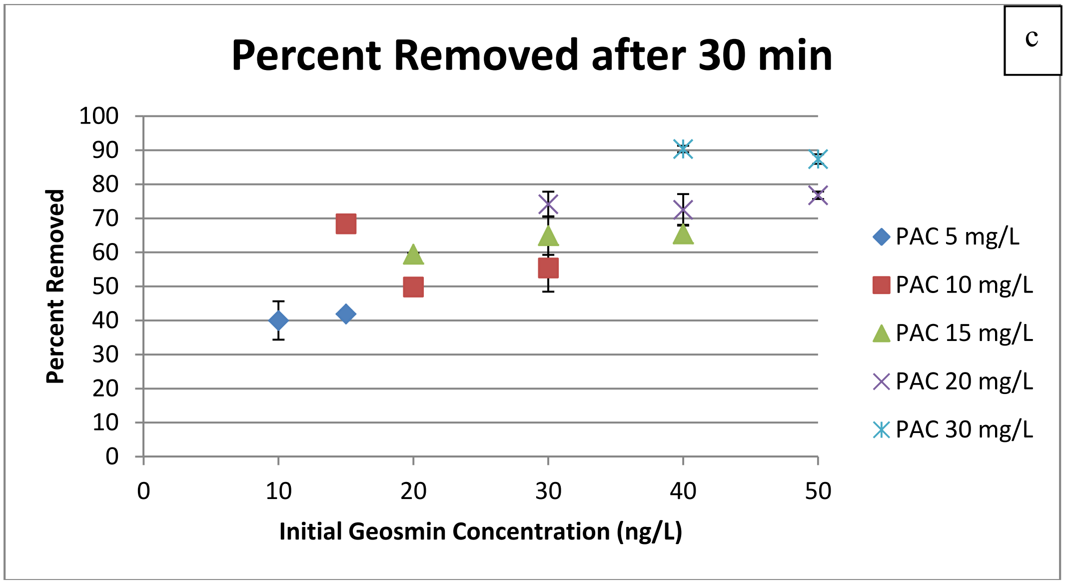
PAC Conc. (mg/L)	GSM Conc. (ng/L)	Contact Time (min)	Measured (ng/L)	Predicted (ng/L)	Std. Dev.	Difference (ng/L)
5	10	15	6.5	7.6	0.773	-1.1
5	15	15	9.5	10.0	0.346	-0.5
10	15	15	8.2	8.1	0.070	0.1
10	20	15	10.4	10.3	0.093	0.1
10	30	15	20.3	14.7	3.959	5.6
15	20	15	9.8	8.1	1.167	1.7
15	30	15	14.8	12.1	1.902	2.7
15	40	15	19.2	16.0	2.280	3.2
20	30	15	11.2	9.5	1.235	1.7
20	40	15	15.9	12.9	2.136	3.0
20	50	15	15.7	16.4	0.525	-0.7
30	40	15	9.9	6.7	2.283	3.2
30	50	15	9.5	9.2	0.225	0.3
5	10	30	5.7	6.7	0.643	-0.9
5	15	30	8.7	8.9	0.101	-0.1
10	15	30	4.7	7.1	1.677	-2.4
10	20	30	9.4	9.1	0.229	0.3
10	30	30	13.6	13.0	0.409	0.6
15	20	30	8.1	7.1	0.719	1.0
15	30	30	10.5	10.5	0.010	0.0
15	40	30	13.7	14.0	0.207	-0.3
20	30	30	7.8	8.1	0.224	-0.3
20	40	30	11.0	11.0	0.001	0.0
20	50	30	11.3	14.0	1.912	-2.7
30	40	30	3.9	5.2	0.916	-1.3
30	50	30	6.3	7.2	0.605	-0.9
5	10	45	5.2	5.8	0.392	-0.6
5	15	45	7.7	7.7	0.022	0.0
10	15	45	3.8	6.1	1.689	-2.4
10	20	45	7.9	7.9	0.052	0.1
10	30	45	11.0	11.3	0.190	-0.3

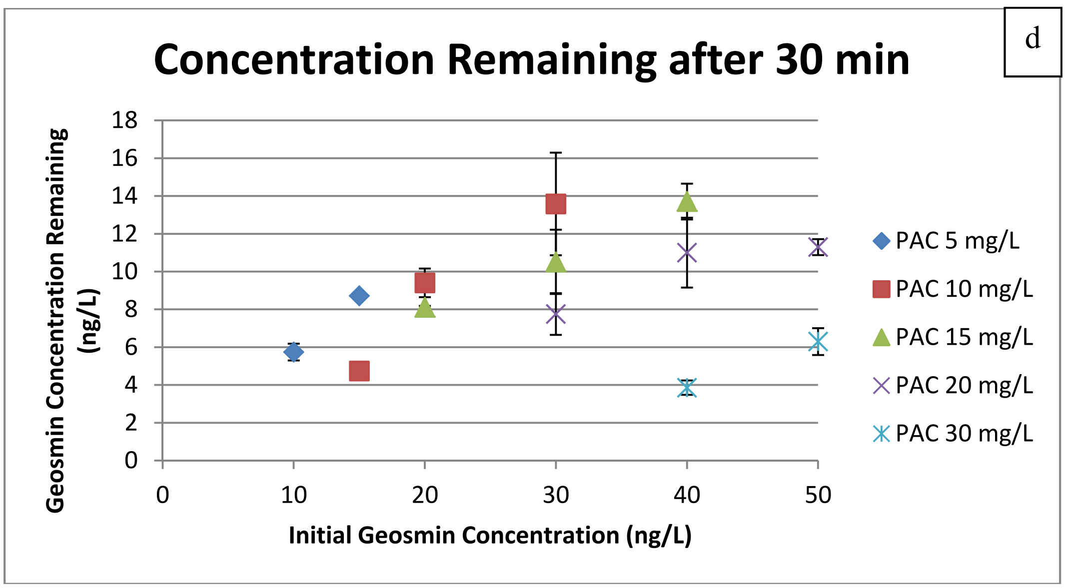
15	20	45	5.9	6.0	0.130	-0.2
15	30	45	7.3	9.0	1.170	-1.7
15	40	45	10.5	11.9	1.000	-1.4
20	30	45	4.5	6.7	1.580	-2.2
20	40	45	7.1	9.2	1.464	-2.1
20	50	45	8.4	11.6	2.230	-3.2
30	40	45	2.6	3.6	0.695	-1.0
30	50	45	4.5	5.1	0.421	-0.6
5	10	60	4.9	4.9	0.001	0.0
5	15	60	6.5	6.6	0.040	-0.1
10	15	60	3.3	5.2	1.325	-1.9
10	20	60	7.1	6.6	0.340	0.5
10	30	60	10.1	9.5	0.390	0.6
15	20	60	4.7	5.0	0.182	-0.3
15	30	60	5.1	7.4	1.639	-2.3
15	40	60	9.3	9.9	0.370	-0.5
20	30	60	2.3	5.3	2.155	-3.0
20	40	60	5.3	7.3	1.372	-1.9
20	50	60	6.7	9.2	1.744	-2.5
30	40	60	2.1	2.1	0.052	0.1
30	50	60	3.4	3.1	0.261	0.4
5	10	90	4.4	3.1	0.903	1.3
5	15	90	6.0	4.3	1.237	1.7
10	15	90	2.9	3.2	0.208	-0.3
10	20	90	5.8	4.2	1.119	1.6
10	30	90	8.0	6.1	1.388	2.0
15	20	90	3.8	2.9	0.662	0.9
15	30	90	3.8	4.3	0.390	-0.6
15	40	90	7.4	5.7	1.150	1.6
20	30	90	1.7	2.6	0.602	-0.9
20	40	90	3.2	3.5	0.207	-0.3
20	50	90	5.9	4.4	1.017	1.4
30	40	90	0.9	0.0	0.670	0.9
30	50	90	2.6	0.0	1.846	2.6

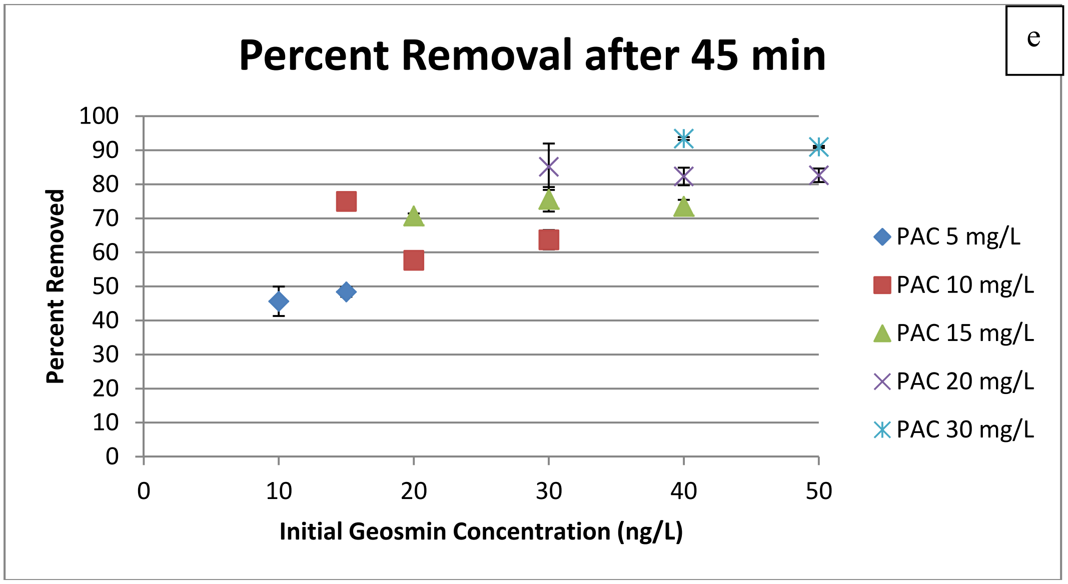
APPENDIX C: GRAPHS FOR PERCENT REMOVED AND CONCENTRATION REMAINING FOR 15, 30, 45, 60, AND 90 MINS

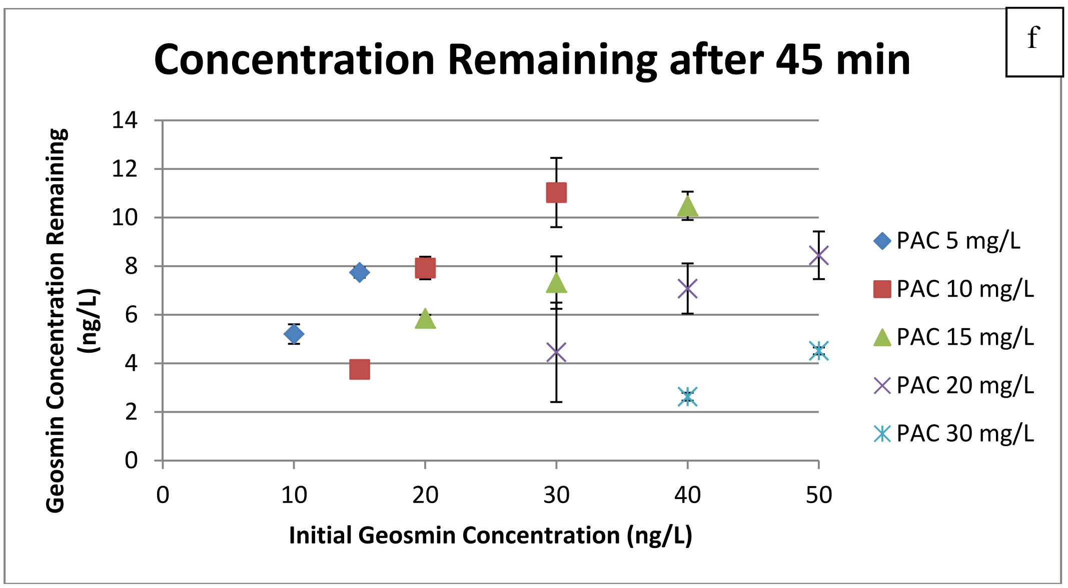


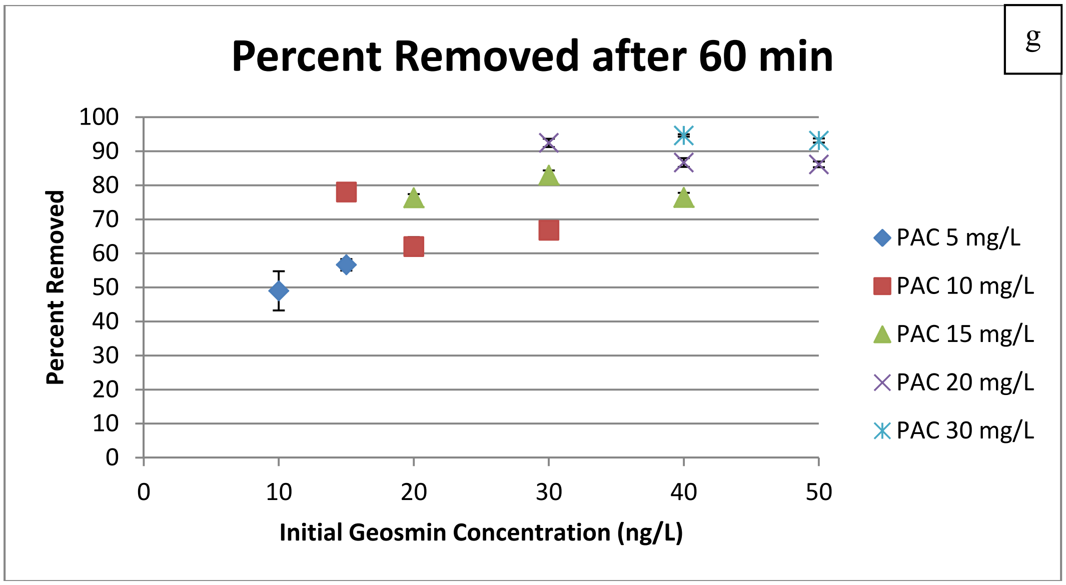


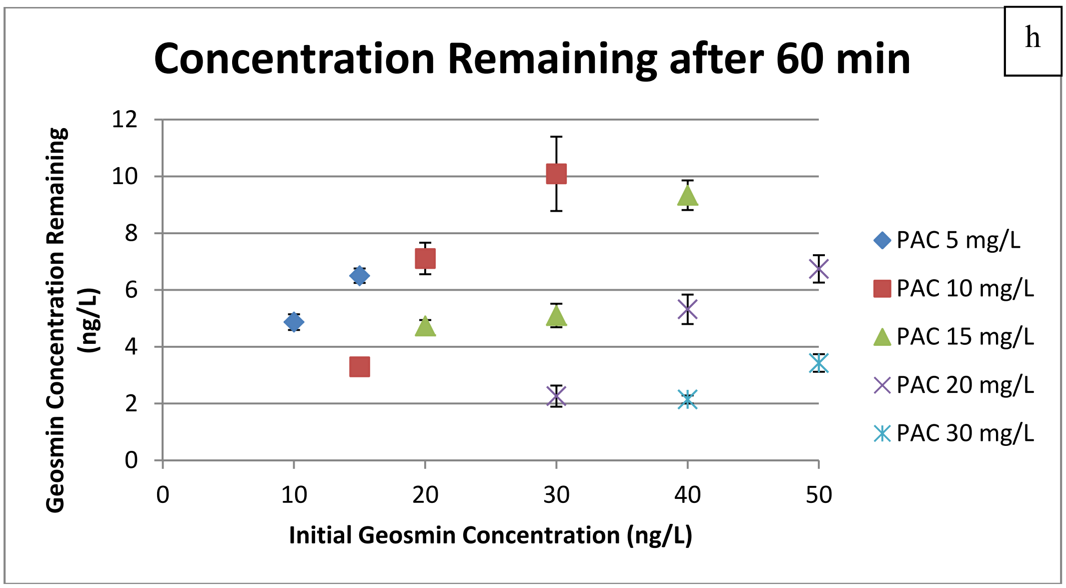

c
Percent Removed after 30 min
Percent Removed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
Initial Geosmin Concentration (ng/L)
PAC 5 mg/L
PAC 10 mg/L
PAC 15 mg/L
PAC 20 mg/L
PAC 30 mg/L

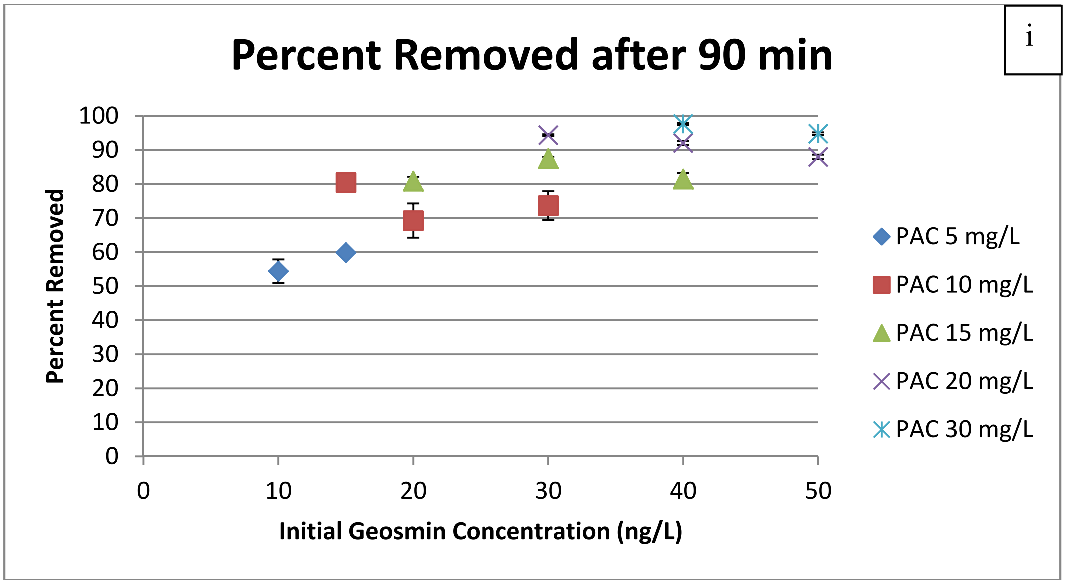

d
Concentration Remaining after 30 min
Geosmin Concentration Remaining (ng/L)
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
Initial Geosmin Concentration (ng/L)
PAC 5 mg/L
PAC 10 mg/L
PAC 15 mg/L
PAC 20 mg/L
PAC 30 mg/L


e
Percent Removal after 45 min
Percent Removed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
Initial Geosmin Concentration (ng/L)
PAC 5 mg/L
PAC 10 mg/L
PAC 15 mg/L
PAC 20 mg/L
PAC 30 mg/L


f
Concentration Remaining after 45 min
Geosmin Concentration Remaining (ng/L)
14
12
10
8
6
4
2
0
0
10
20
30
40
50
Initial Geosmin Concentration (ng/L)
PAC 5 mg/L
PAC 10 mg/L
PAC 15 mg/L
PAC 20 mg/L
PAC 30 mg/L


g
Percent Removed after 60 min
Percent Removed
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
Initial Geosmin Concentration (ng/L)
PAC 5 mg/L
PAC 10 mg/L
PAC 15 mg/L
PAC 20 mg/L
PAC 30 mg/L


h
Concentration Remaining after 60 min
Geosmin Concentration Remaining (ng/L)
12
10
8
6
4
2
0
0
10
20
30
40
50
Initial Geosmin Concentration (ng/L)
PAC 5 mg/L
PAC 10 mg/L
PAC 15 mg/L
PAC 20 mg/L
PAC 30 mg/L



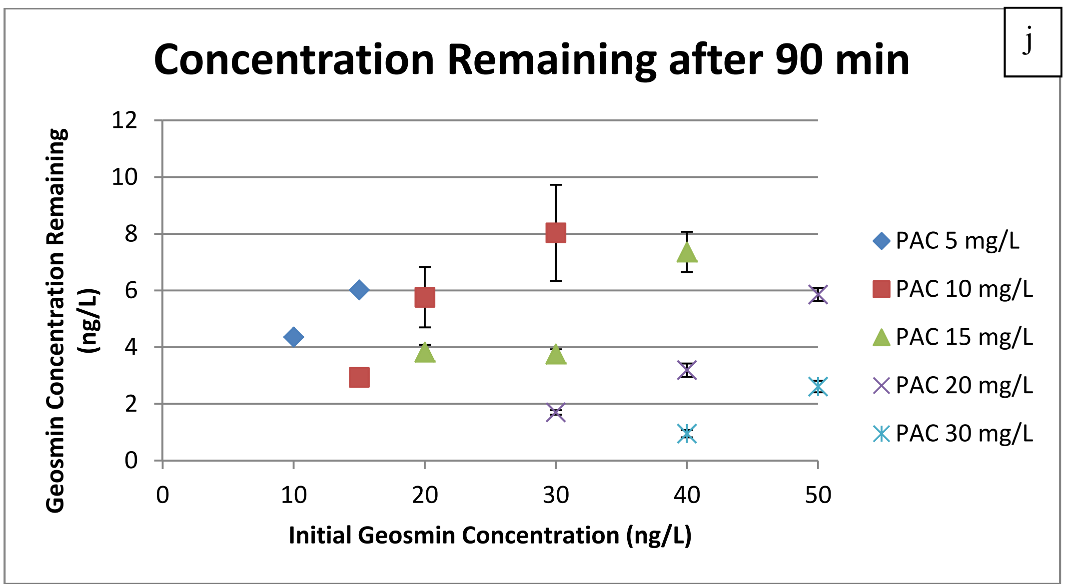


Figure D.1: Graphs of Percent Removed and Geosmin Concentration Remaining for 15, 30, 45, 60, and 90 Minutes