

**High Surface Area of Small Pumice Heightens Filtration Efficacy: Successful Experimental
Applications of Pumice as Column Filter Media for Synthetic Graywater**

by

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A thesis accepted and approved in partial fulfillment of the
requirements for the degree of
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THESIS ABSTRACT

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Master of Science in Earth Sciences

Title: High Surface Area of Small Pumice Heightens Filtration Efficacy: Successful Experimental Applications of Pumice as Column Filter Media for Synthetic Graywater

Graywater is wastewater from non-sewage domestic sources like bathing, dishwashing, laundry, and cleaning. Contaminant particles from shampoo, detergent, and other household products can be removed through granular filtration systems using material such as gravel or sand. Many natural materials have been proposed for use as graywater filters; this project tests different sizes of pumice, a porous volcanic rock. After characterizing physical properties of five different size fractions of pumice from the ~7,700 ka Climactic eruption of Mount Mazama, Oregon, we applied the pumice as a filtration medium in a granular column flow experiment and monitored graywater chemistry for seven days. Our experiments suggest that pumice effectively filters contaminants from graywater within 48 hours of column filtration flowing at ~10 liters per hour. We also find that, among the five sample sizes tested, the smallest, 1-2 mm, pumice particles are the most effective. Filtration with this size of rock results in significant reductions of turbidity, total nitrogen, phosphate, and chemical oxygen demand in the graywater over seven days. We believe this size range is the most effective filter because of its higher external surface area over volume ratio compared to larger sizes of pumice. These results suggest that small 1-2 mm pumice would be the most effective if applied to create real-world graywater filtration systems. More work remains to be done to understand the logistical needs and practical lifespans of these pumice systems.

A HAIKU

cleaning graywater?

small pumice filters better.

thank you, surfaces!

CURRICULUM VITAE

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Price, M.B., McCleskey, R.B., Nordstrom, D.K. (2024, March 18). Exploring 140 years of water chemistry research in Yellowstone National Park. *Yellowstone Caldera Chronicles*. <https://www.usgs.gov/observatories/yvo/news/exploring-140-years-water-chemistry-research-yellowstone-national-park>

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WITH GRATITUDE

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1. INTRODUCTION

1A. WASTEWATER TREATMENT & GRAYWATER SYSTEMS

We produce graywater every day of our lives. *Graywater* (non-sewage domestic wastewater) contains a diverse range of constituents, including personal care products like soap, shampoo, and makeup, cleaning supplies like bleach and detergent, solid materials like toothpaste, clothing fibers, and soil, and anything else that goes down the drain (*Figure 1*). Wastewater from our homes thus contains both graywater and *blackwater*: sewage from toilets containing fecal matter. Typically, graywater is estimated to make up between 65-75% of a household wastewater by volume (Ghaitidak & Yadav, 2013; EPA, 2017; Liberman et al., 2015). However, the precise chemical makeup and specific proportions of graywater to blackwater of each household varies based on the products used by its inhabitants, as well as their cleaning, water use, and personal care habits.

Due in part to the diverse range of materials that go into creating it, graywater typically contains several types of contaminants (Abedin & Rakib, 2013; Athullya et al., 2021; Benami et al., 2016; Oteng-Peprah et al., 2018; Rose et al., 1991; Sievers & Londong, 2017). These can include large solid pieces like lint, hair, and food particles, suspended and dissolved solids, assorted chemicals and nutrients, organic materials, fats, oils, and greases, pharmaceuticals, and harmful bacteria, among others (Allen et al., 2010). Contaminants like these, and the more harmful components from sewage found in

blackwater, must be removed from wastewater before it is discharged into watersheds, or risk harm to environmental and human health.

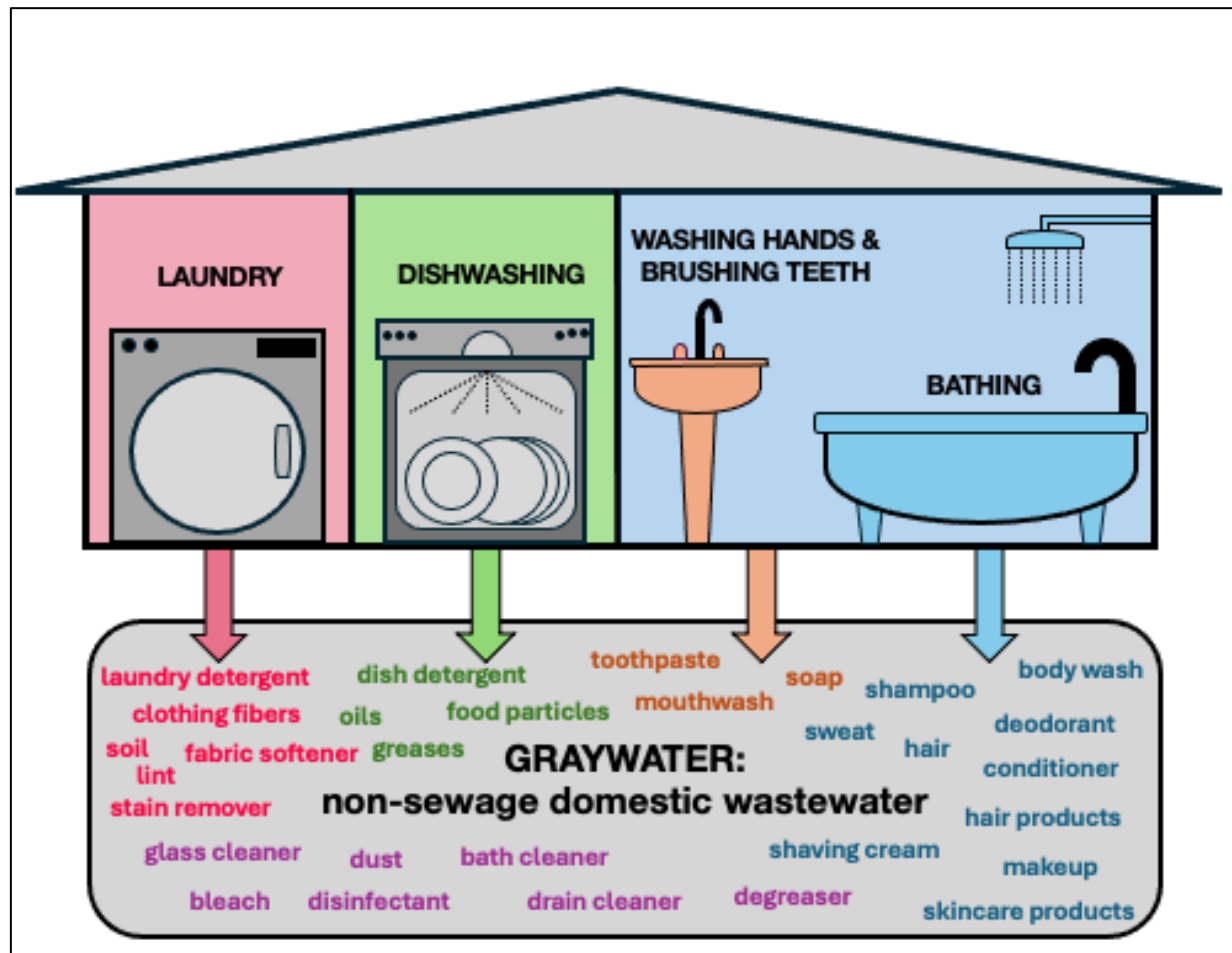


Figure 1: Graywater sources & contaminants

Graywater is non-sewage wastewater domestic wastewater from washing clothes, dishes, and hands, as well as bathing, brushing teeth, and cleaning. Components within graywater can vary geographically or socially, depending on the appliances and products used as well as the water use habits of the inhabitants.

1A.i. Conventional Wastewater Treatment Methods

Nearly 80% of households in the United States are connected to municipal sewer systems and about 20% to individual domestic septic systems (EPA, 2015). After use, wastewater from these homes is pumped to treatment plants, where it is subjected to a combination of physical and chemical treatment methods before being released, typically into local watersheds.

Wastewater in the Eugene-Springfield metropolitan area is treated by the Metropolitan Wastewater Management Commission, a regional organization which serves the area's roughly 220,000 customers. MWMC's Regional Wastewater Treatment Plant (*Figure 2*), in north Eugene, cleaned around 32.8 million gallons of water per day on average in 2022, totaling around 12 billion gallons (MWMC). The city's public water, which comes from the McKenzie River, is used in homes, businesses, and other buildings, and then pumped to the treatment station. There, the *influent* (incoming, untreated wastewater) flows through grit chambers and screens to remove large objects before the "primary treatment" stage, in which smaller solids settle out through gravity. These "biosolids" are removed from the primary treatment tanks and turned into soil amenities for use at the city's Biocycle Farm, which grows and sells a grove of poplar trees (MWMC). Next, the wastewater is aerated with bacteria to decompose remaining organic matter before "secondary clarification," which repeats the primary clarification process. MWMC is currently developing a further "tertiary" phase of treatment, using filters to remove any small solids remaining in the wastewater. Lastly, the water is disinfected using chlorine, which is then removed before the effluent is released into the Willamette River.

This system, with combinations of physical filters, biologic treatment, and chemical disinfection, is consistent and effective, removing more than 97.5% of pollutants and recognized in 2021 and 2022 by regional and national regulatory bodies for environmental and plant safety (MWMC). For more descriptions of the processes taking place in this and other conventional wastewater treatment plants, see **Appendix I**.

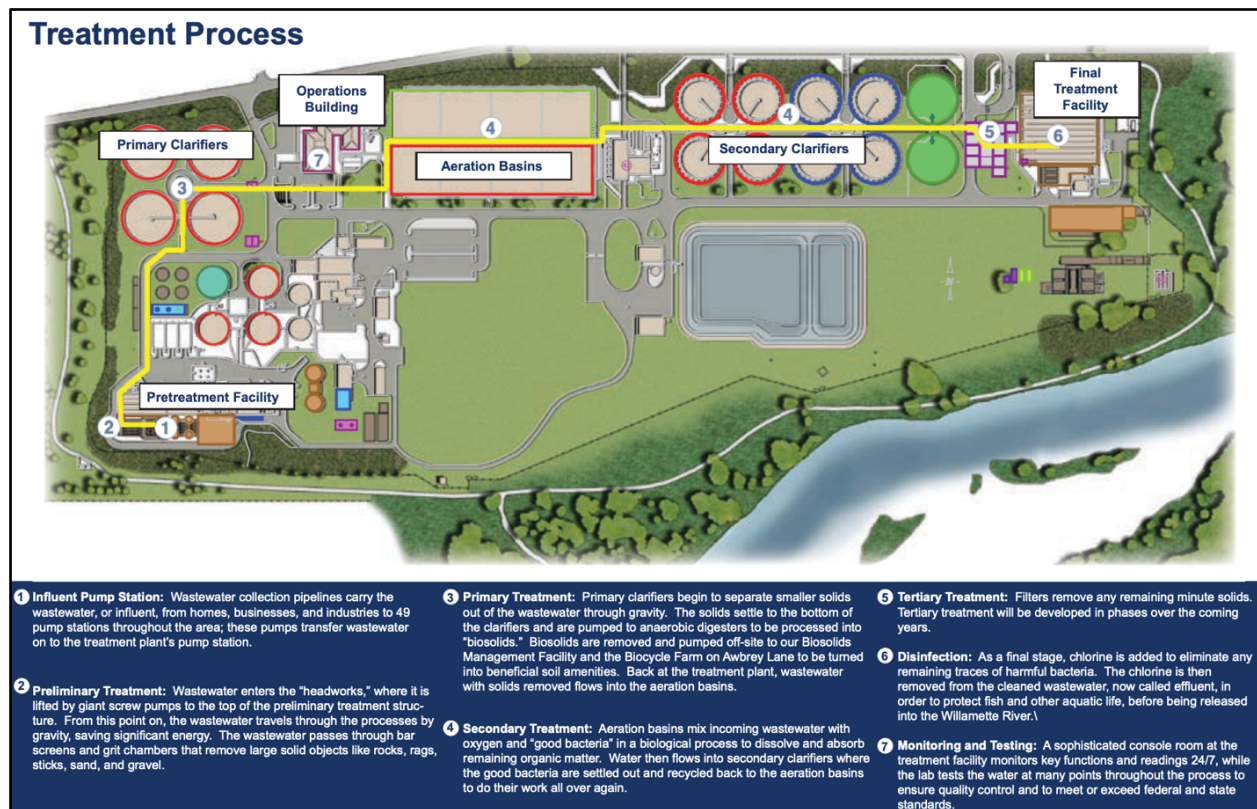


Figure 2: Site map of MWMC Water Pollution Control Facility

Wastewater treatment at the MWMC (Metropolitan Wastewater Management Commission) follows conventional methods: pretreatment with large filters and screens, primary treatment with anaerobic digestion and clarification, secondary treatment with the addition of "good" bacteria and further clarification, tertiary treatment with further filtration, and disinfection prior to release.

1A.ii. Water Usage and Potential for Graywater Recycling

In 2015, agricultural irrigation consumed 42% of freshwater withdrawn in the United States (Dieter et al., 2018). In many circumstances, the freshwater used for irrigation and gardening could be replaced with treated wastewater effluent– this change would reduce the amount of freshwater being withdrawn, extending the longevity of existing surface water and groundwater resources and lowering the societal footprint on hydrogeologic systems already strained by population growth and global climate change (Nelson, 2014). In addition to irrigation and gardening, reused wastewater can be used for other tasks which don't require potable water, such as washing vehicles, buildings, streets, and patios, and flushing toilets and urinals (Ekeren et al., 2016; NAS 2016; Mourad et al., 2011; Ren et al., 2018; Penn et al., 2012). Recycled wastewater can also be used to recharge non-potable groundwater aquifers, in industrial cooling towers, for fire extinguishing, to augment wetlands habitat for wildlife, to fill artificial lakes, and for construction tasks like concrete mixing (Pazwash, 2011; Ghunmi et al., 2011).

Graywater is a prime candidate for treated wastewater reuse. Contaminants in graywater are less harmful than the contaminants in sewage blackwater, and it is generally easier to treat graywater to a usable (albeit non-potable) degree of sanitation. In many places across the world, including much of the United States, there are already well-established precedents for recycling both treated and untreated graywater– parts of Europe and arid regions of the US, where water shortages are common, have been reusing wastewater for decades (Pazwash, 2011). Implementation of graywater reuse systems is possible on both municipal and individual levels: many of the wastewater treatment methods listed above

can be implemented by households. Even using treated household graywater to just flush toilets can reduce wastewater output by 26-35% (Mourad et al., 2011; Penn et al., 2012). Adding garden irrigation can bring wastewater output reduction to 41% (Penn et al., 2012).

It is no surprise that in arid, more drought-prone regions, where water resources are limited, graywater and wastewater recycling is encouraged. Graywater recycling is, in fact, allowed in much of the United States: 75% of Americans live in states where graywater recycling is permitted, with more than 50% living in states where either there is no permit required or rules surrounding permits are unclear (*Figure 3*). Not all states and territories consider graywater equally, though. The state of Maryland defines graywater as bathing and sink effluent only, whereas others (Arizona, Delaware, and Massachusetts) require repurposed graywater to be dyed for differentiation from potable water, while still others (17 in total) do not allow graywater to be recycled or separately treated at all.

References for this information and for *Figure 3* can be found in **Appendix II**.

In Oregon, individual household graywater systems have been permitted by the Oregon Department of Environmental Quality (DEQ) since 2011 (Heins, personal communication). As of 2022, only 53 permitted domestic graywater systems had been implemented in the state, more than 40 of which were simple laundry reuse systems where untreated or minimally treated laundry wastewater is piped to an outdoor agricultural irrigation network. It is estimated that there are likely many more unregulated graywater reuse systems in the state which are not in compliance with or officially registered with the state DEQ (Heins, personal communication).

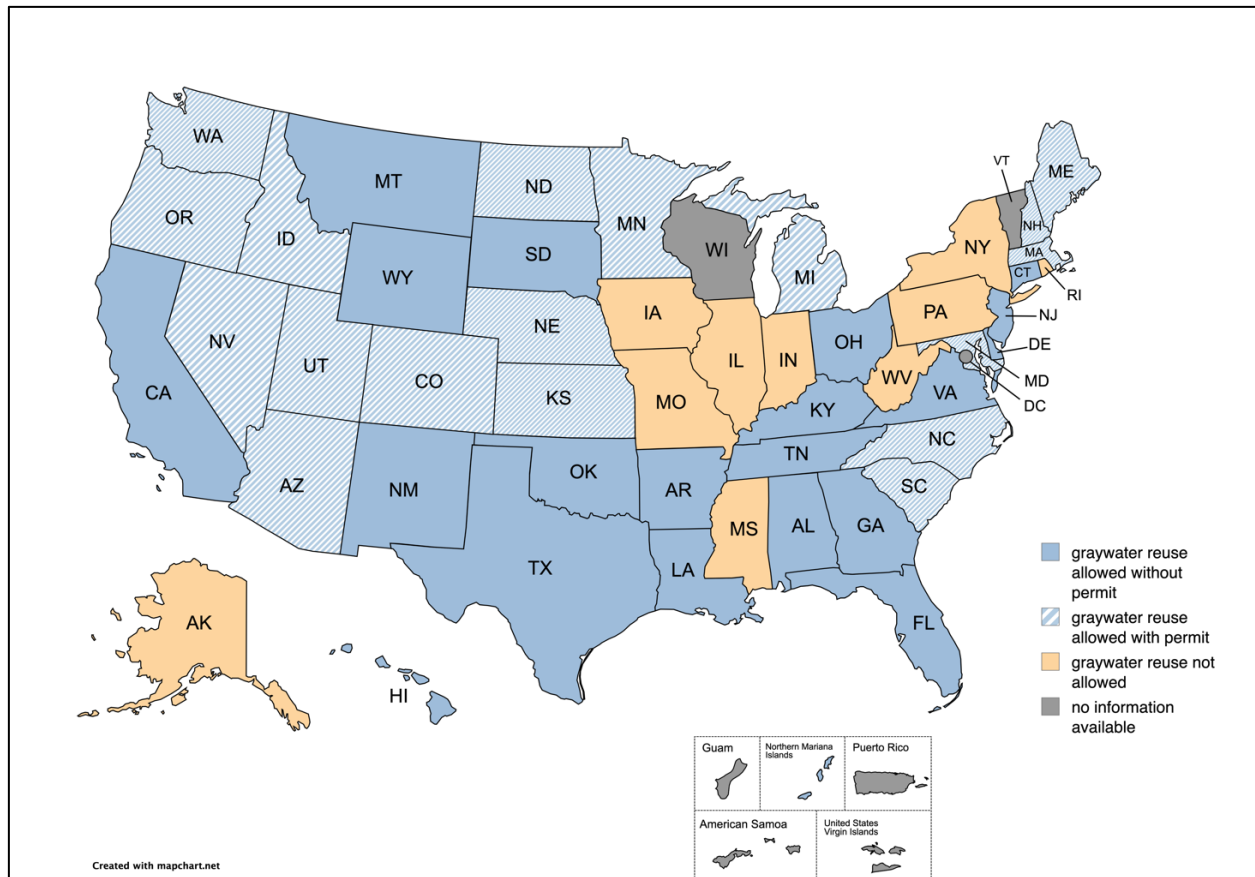


Figure 3: Graywater reuse laws in the United States

Graywater laws vary based on state and county regulations. This map shows the legal status of graywater recycling across the U.S. and its territories. Data could not be located for Guam, Puerto Rico, American Samoa, the U.S. Virgin Islands, Wisconsin, Washington, D.C., or Vermont.

1A.iii. Graywater Treatment in the Literature

Researchers across the world have investigated numerous different methods to treat graywater. Some systems use conventional electrochemical or chemical wastewater treatment methods, such as electrocoagulation, reverse osmosis, and UV disinfection (Bajpai et al., 2020; Boano et al., 2019; Kabiri et al., 2021; Kim et al., 2009; Lalley et al., 2023; Liberman et al., 2015; Ramon et al., 2004; Shaikh & Ahammed, 2021). Many others, however, replace or pair those methods with simpler and lower-cost techniques,

such as granular filtration and constructed wetlands systems using natural materials.

Graywater is also sometimes reused directly with minimal treatment for uses such as irrigation of vegetable plants (Misra et al., 2010).

Granular filtration systems consist of horizontal or vertical beds of coarse sediment, through which graywater flows (

Figure 4). As the water flows through the system, contaminants are trapped on the surfaces of the grains, leaving behind cleaner effluent. Granular filtration conventionally includes beds of gravel, soil, and/or sand (Boyle et al., 1983; Hachicha et al., 2022; Tusiime et al., 2022). However, in the interest of economic and practical feasibility, a wide variety of materials have been used– including but not limited to volcanic tuff, activated carbon, coconut coir and shell fragments, sawdust, bricks, tree bark, corrugated plastic, bark mulch, biochar, charcoal, compost, limestone, dolomite, clamshells, and steel slag (Albalawneh et al., 2017; Astuti et al., 2017; Boano et al., 2019; Mohamed et al., 2016; Rafiq et al., 2024).

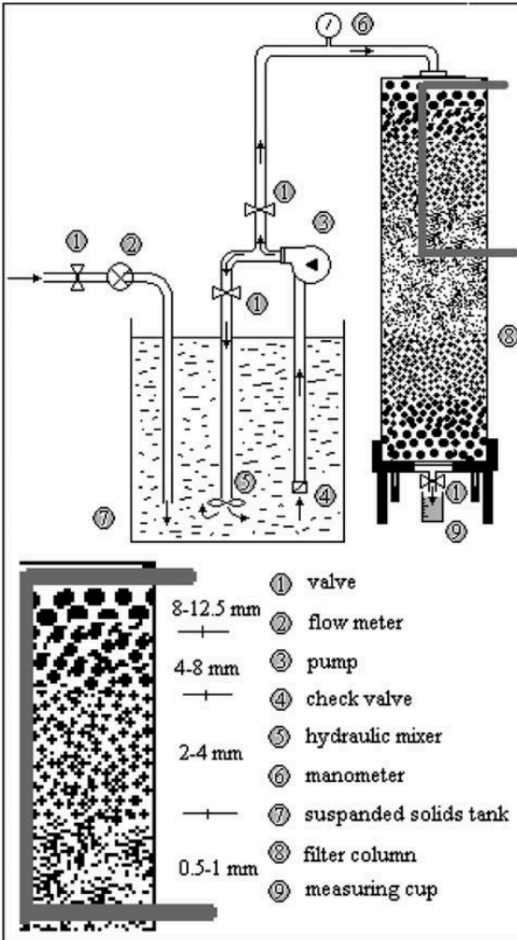


Figure 4: Granular filtration system from literature

Granular filtration systems consist of influent flowing through a container of pieces. Contaminants are trapped on the surfaces of these grains. These systems commonly include layers or sections of different sizes or types of grains and have been tested with a wide range of natural and synthetic materials. (From Kuslu & Sahin, 2013).

Constructed wetlands systems include a vertical or horizontal bed of coarse grains, in which plants are grown (Figure 5). The graywater flows in a controlled manner through the system, simultaneously being filtered by the sediment and by physical and biochemical interactions with the plants and their roots. This method is commonly used in both experimental and real-world graywater treatment systems; the wetland-filtered effluent is often subjected to secondary treatment such as UV disinfection to remove further microbial components before reuse or release (Astuti et al., 2017; Chowdhury et al., 2018; Hachicha et al., 2022; Laaffatt et al., 2017; Tusiime et al., 2022).



Figure 5: Examples of constructed wetlands systems (A) from Aregu, 2022; (B) from Chowdhury et al., 2018.

Constructed wetlands systems add plants to the framework of the granular filtration method– removing contaminants through both surface area interactions with the granular medium and biochemical interactions with the plants and their root systems. Wetlands systems are popular for real-world graywater treatment in part for their adaptability– the type of plant(s) used can be customized to reflect climatic and ecologic needs of any area, as well as support the use of native flora in community infrastructure.

1A.iv. Real-World Graywater Filtration Projects

Communities around the world already use a wide range of graywater treatment technologies to reduce water consumption, decrease environmental pollution, and improve local infrastructure. For example, Community Supported Shelters (CSS), a nonprofit organization in Eugene, Oregon which provides temporary group living communities for houseless populations, utilizes experimental graywater systems that take graywater from communal hand-washing stations and kitchen sinks and treats it using a combination of chemical disinfection and constructed wetland flow (*Figure 6*) – with some of the wetland substrate being pumice! This system is ideal for CSS because the living communities are often located on land plots without traditional sewer, water, and electric

hookups– meaning that potable water must be transported in and wastewater must be transported out (Russel, personal communication). Having on-site graywater filtration, which reduces the need to transport out wastewater, lowers costs for CSS while also creating opportunities for future garden projects where treated graywater could be used to water plants for aesthetic appeal, shade, or food.



Figure 6: Graywater filtration system at a CSS site in Eugene (2024)

At this and other CSS sites across Eugene, water from a kitchen sink and from hand washing flows from left to right into the first tank of plants in sediment. From there, it flows into the blue buckets where it is disinfected, then flows again through the pumice wetland tank on the far right.

Further applying the principles of constructed wetland graywater filtration is LeapFrog Design, a Bend-based company co-founded by former University of Oregon graduate

students which sells home graywater treatment systems designed as benches and planter boxes— simultaneously treating household graywater while also growing ornamental plants! Each planter box module of the “Estuary” model (*Figure 7*) can filter 50 gallons of graywater daily, and, according to the company, the system is estimated to save 270,000 gallons of water, 2 tons of carbon dioxide emissions, and \$8,000 in water costs over ten years. LeapFrog also works with low-income communities around Lima, Peru to design graywater treatment and reuse systems which can be locally managed and return usable treated effluent to the communities (*Leapfrog*).



Figure 7: LeapFrog Estuary domestic graywater treatment system (LeapFrog)

Graywater from the house flows into the storage tank (left module with the bench top), then cycles through the pumice in the wetland system (right module growing plants).

1B. PUMICE AND ITS APPLICATION AS A WASTEWATER FILTER

1B.i. Pumice Formation and Porosity

Pumice is a light, porous rock made of volcanic glass (*Figure 8-A*). Typically formed in explosive silicic eruptions, pumice's foamy texture (*Figure 8-B*) is a result of decompression and ensuing exsolution of gas (mostly water) within the magma as it ascends through the conduit towards the Earth's surface (*Figure 9*). This texture is then "quenched" (i.e., frozen) as the magma rapidly cools down near the surface. Although some of the air bubbles, or "vesicles," formed within the magma remain isolated from one another (being surrounded by rock), most are joined together, creating networks of interconnected bubbles through which gas can flow and ultimately get outside of the pumice fragment. (Each individual pumice fragment is called a "clast").

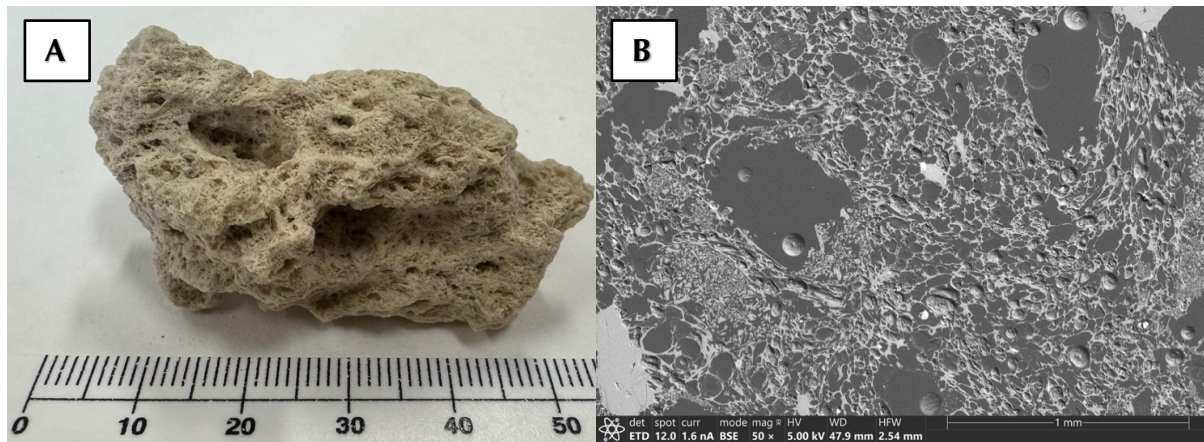


Figure 8: Photograph and backscattered electrons Scanning Electron Microscope (SEM) image of Mazama Climactic pumice

(A) A ~50-mm clast of Mazama Climactic pumice with large and small visible pores.

(B) SEM image of 8-16 mm Mazama Climactic pumice photographed with the assistance of Kurt Langworthy 2022 in the UO Knight Campus SEM using 50x magnification. The lighter gray material is solid phase rock, while the dark gray material is void space.

Volcanoes around the world generate pumice deposits centimeters to tens of meters thick, dispersed across hundreds to thousands of square kilometers, and made of clasts ranging from millimeters to centimeters in size. Eight hundred million people around the globe live in or near volcanic areas such as Andean South America, Indonesia, Japan, East Africa, New Zealand, the U.S. Pacific Northwest, and Iceland, among others (Brown et al., 2015). As a foundational and prominent component of the landscapes in parts of these locations, pumice deposits are both easily accessible and relatively low-cost to residents of these volcanically active regions.

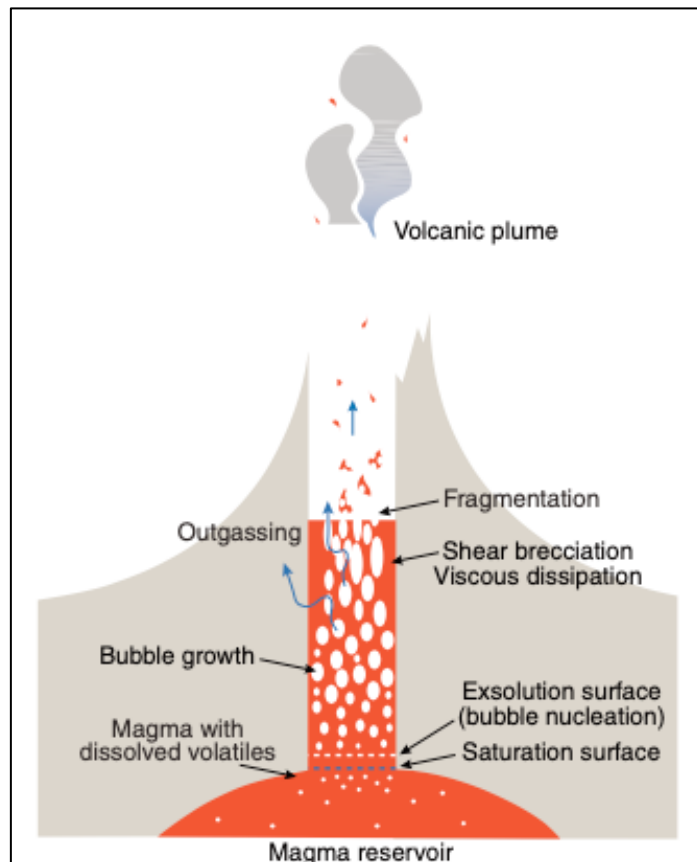


Figure 9: Fragmentation of magma into pyroclasts

As melt rises through the conduit, it transforms into a mixture of gas and blobs of magma called pyroclasts in the process of “fragmentation.” From Gonnermann and Manga, 2015.

1B.ii. Applications of Pumice as a Wastewater Filter

Several characteristics of pumice make it an ideal candidate to use as a granular filtration material. Firstly, because all people use water and thus produce wastewater, treatment methods need to be both physically and financially accessible– because it is produced at volcanoes around the world, pumice is a feasible filtration material for countless communities. Secondly, and more importantly, pumice’s high interconnected porosity theoretically increases its surface area: water flowing through a granular filter of pumice can not only contact the surfaces on the outside of each clast, but also with the surfaces on the inside of all the clast’s interior interconnected vesicles which it can reach.

Furthermore, this available pore space also increases the filtration system’s capacity to hold water, since water can be stored not just in the interstitial spaces between clasts, but also within the clasts themselves. This means that granular filters made of pumice can, in theory, support more rapid and effective filtration than filters with identically-sized but non-porous filter particles. Lastly, when dry, pumice is extraordinarily light– so light, in fact, that the rock is famous for floating on water. This means that even large volumes of pumice are easy to lift and transport– making large-scale filtration projects more practically attainable.

Pumice has been proven an effective filter for several other types of wastewater, including from olive mills, tanneries, and other heavily-contaminated industrial sources. The rock has been successfully used to remove suspended solids and clays (Farizoglu et al., 2003,

Kuslu & Sahin, 2013), phenol (Heydari et al., 2018), harmful chemical gases (Kam et al., 2011), and heavy metals (Aksay & Akar, 2010; Aregu, 2017; Aregu et al., 2018; Aregu et al., 2021; Aregu, 2022; Asere et al., 2017; Bilardi et al., 2013; Kelm et al., 2003; Khorzughy et al., 2014). Meaningful removal of these and other kinds of contaminants has proven that pumice's filtration efficacy is comparable to other, more conventional granular filter media like gravel and sand.

Despite its demonstrated use in treating other types of wastewater, pumice has rarely been applied as a filter for graywater specifically. This gap in the literature should be explored more, as it is clear that pumice could be an effective material for graywater treatment.

1C. PROJECT INTRODUCTION

This master's project, an extension of my 2022 undergraduate thesis, explores the use of pumice as a filtration medium for synthetic graywater. Given the environmental and societal benefits of graywater treatment and reuse, and the successful use of pumice as an effective granular filtration material for other kinds of contaminated wastewater, it seems intuitive to study in further depth the application of pumice as a graywater filter so that it can be compared to other materials and filtration methods. This project uses **United States Pacific Northwest-sourced pumice** to filter **synthetic graywater** made in the laboratory, cycling the graywater through a **pumice-filled column filtration system for seven days** and monitoring physical and chemical parameters in the graywater over time.

The pumice used in this project was collected from deposits of the Climactic eruption of Mount Mazama, a well-known stratovolcano in the Oregon Cascades. Around 7,700 years ago, Mazama (called *Tum-se-ne* by the indigenous Klamath people prior to its eruption) experienced a large caldera-forming eruption, blanketing much of the North American continent with 176 cubic kilometers of pumice and ash (Alatorre, 2021; Bacon & Lanphere, 2006; Buckland et al., 2020; *Figure 10*). Over the last several thousand years, the caldera has filled with water and now holds the famous Crater Lake (*giiwas* in Klamath) Today, ash and pumice deposits from the Climactic Mazama eruption can be found across the western United States and southwestern Canada, including underneath forests, estuaries, and other ecosystems. The wide distribution of this pumice, which is both low-cost and easy to obtain, makes it a compelling candidate material for graywater filtration, especially here in the Pacific Northwest.

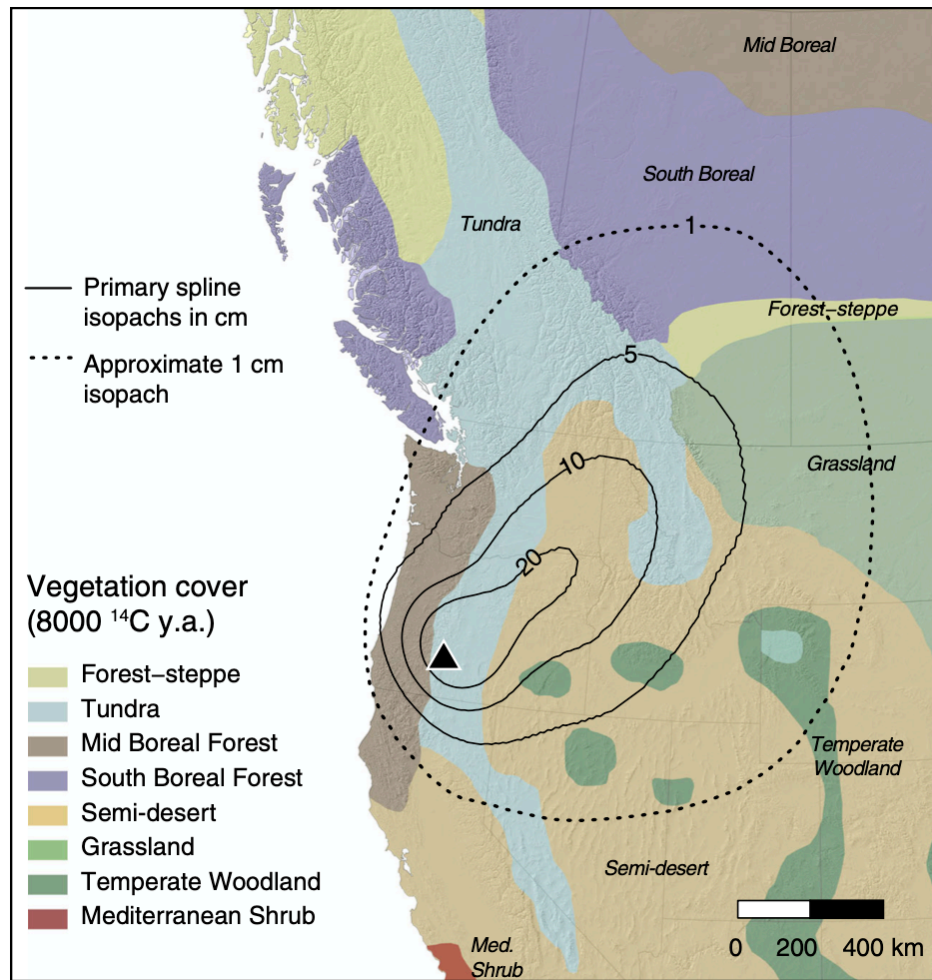


Figure 10: Map of Mazama Climactic tephra fall across western North America

From Buckland et al., (2020). The Climactic eruption of Mount Mazama / giiwas, around 7,700 years ago, erupted 176 cubic kilometers of pumice and ash, with deposits reaching into what is now Washington, Idaho, Montana, Wyoming, Utah, Nevada, California, and parts of Canada. This figure, from Buckland et al., (2020), shows isopachs (lines of equal deposit thickness) of the Climactic eruption deposit on top of the type of vegetation which was present at the time of the eruption.

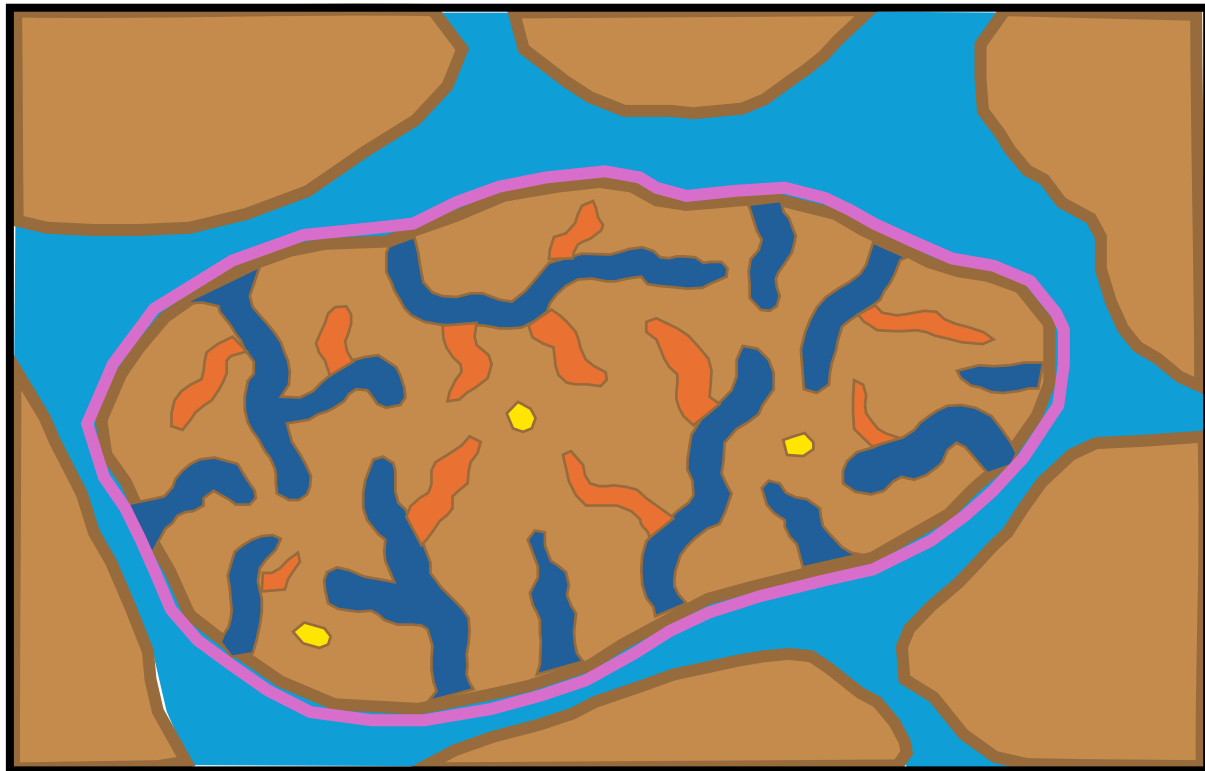
In this thesis, we discuss changes in graywater chemistry which occur during filtration through columns filled with pumice, then unpack the physical characteristics of the pumice which affect these changes. This nexus of wastewater filtration and volcanology, while excitingly interdisciplinary and wide-ranging, can bring with it some confusion

surrounding vocabulary terms that carry alternate meanings in different fields of research.

See *Table 1* and *Figure 11* below for definitions of key terms used throughout this thesis.

Table 1: Key terms used throughout this thesis

<i>term</i>	<i>definition</i>
<i>ash</i>	Small (<2 mm) volcanic material, also referred to as “fine ash”
<i>clast</i>	One single piece of pumice
<i>particle</i>	Piece of contaminant found in graywater
<i>sediment</i>	Solid material that is suspended in or has settled out of graywater



Term	Definition
Water-accessible Connected Pores	Connected pore space within the rock that can be reached by water during flow
Water-Inaccessible Pores	Connected pore does not store water during flow due to being too small or tortuous for water to reach
Isolated Pores	Pore space sealed off from the outside
Interstitial Space	Void space in between pumice clasts
Surface Area	Amount of area on external surfaces of clast (cm ²)

Figure 11: Types of surfaces and spaces between and around pumice clasts

Connected porosity is split into accessible (dark blue), which is space accessible to water during our experiments, and inaccessible space (orange), which is pores which are accessible to helium but not water due to being too small or tortuous for water to reach. Isolated pores are yellow. Interstitial space (light blue) is the void space between clasts, which is filled by water during column flow. The purple coloring around the edge of the clast represents its surface area– the amount of external space on its outside surfaces.

2. PUMICE AND GRAYWATER CHARACTERIZATION METHODS

This project encompasses data from multiple sets of rock-water interaction experiments, conducted throughout my undergraduate and graduate programs from 2021 through 2024. Each set of experiments began with detailed characterization of the rocks in the Giachetti Physical Volcanology lab and the creation of synthetic graywater. Characterizing the pumice allows us to better understand the columns the graywater is flowing through—how much rock is present, how much and what kind of surface that rock contains, and how much space exists between rocks within the columns.

I detail below the methods used for these procedures and analyses.

2A. Pumice Sample Collection and Preliminary Laboratory Analyses

In the field of physical volcanology, samples of tephra, like pumice and scoria, are typically collected through digging pits in eruptive deposits (*Figure 12*). These pits are sometimes hand-dug with shovels and can be up to a few meters deep, allowing for sampling of every layer of a volcanic tephra deposit; however, other methods for sample collection involve excavating using heavy machinery or purchasing sample directly from a quarry. Following photographic documentation of a pit site, samples are typically collected in bags and brought back to the laboratory, where they are dried using an oven at around 120° C. The samples used in our work are also gently washed to remove ambient ash and soil. Organic material, like root fibers, is removed by hand when possible. Then, our samples are sorted using metal sieves into 0.5-1 mm, 1-2 mm, 2-4

mm, 4-8 mm, 8-16 mm, and 16-32 mm size ranges. During the sieving process, fragments of lithics or obsidian that are large enough to be identified are removed (because these experiments specifically investigate pumice). This removal is feasible for grains > 2 mm but becomes impractical– and thus is not carried out– for grains < 2 mm.

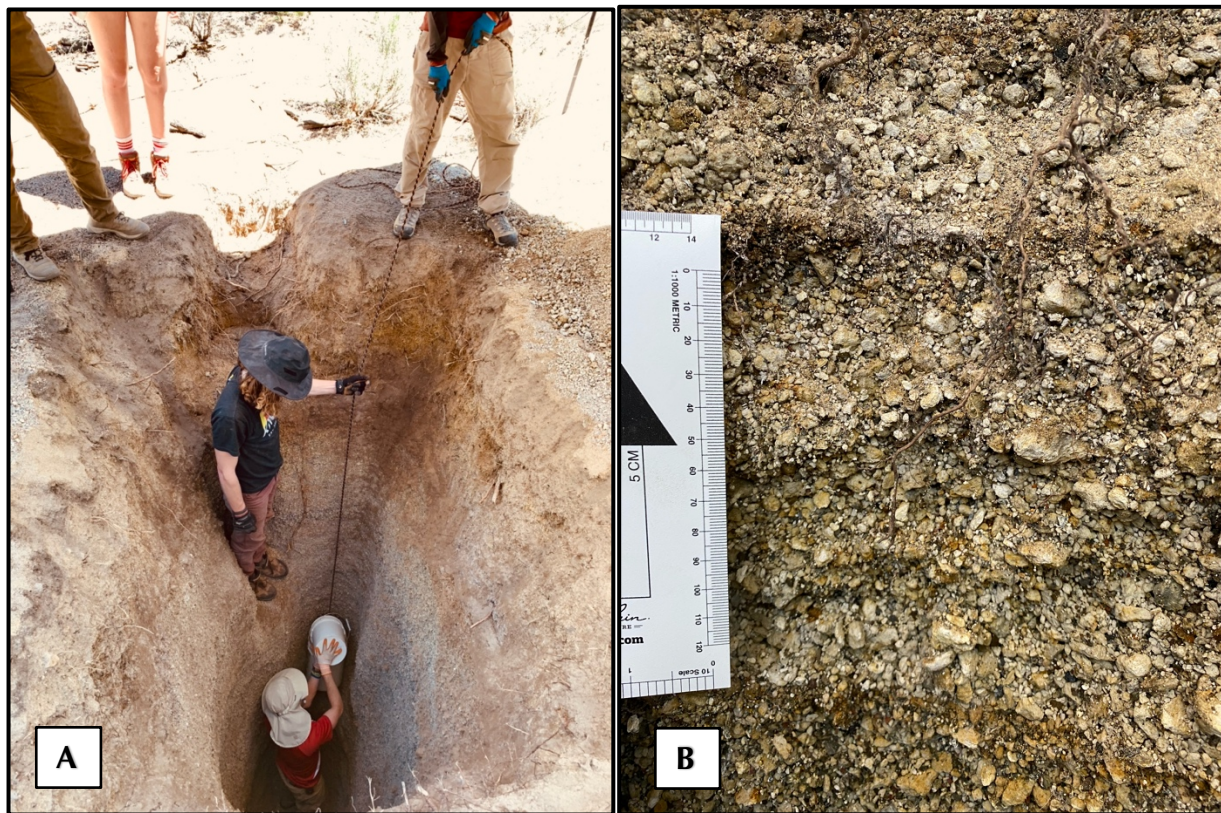


Figure 12: Tephra pits in Cascades eruption deposits

(A) Tephra pit in Mazama Climactic pumice deposits, June 2022. Students at UO Physical Volcanology Field Camp are using buckets, ropes, and shovels to dig a ~5 m deep tephra pit, lovingly titled “Mega Pit” through layers of the Mazama Climactic deposit.

(B) Close-up view of pumice and ash layers in Newberry Pumice (~1300 years before present) deposits with scale card, also from UO Field Camp, June 2022.

We also conduct basic componentry analyses of the 1-2 mm size fraction, in which 100 clasts are counted and identified as either pumice or “lithics”– chunks of rock or obsidian

which were deposited in the same eruption event but are not porous and as such are denser than pumice.

2B. Dimensional Sample Analysis

Pumice samples are analyzed in a physical volcanology lab using the MicroTrac PartAn^{3D} Particle Size Analyzer (hereafter referred to as “PartAn”), an instrument (*Figure 13*) that utilizes dynamic image analysis to measure physical characteristics of grains. Granular samples are placed on an elevated vibrating metal tray, which directs the clasts to fall across the view of a high-resolution, high-speed camera. This camera captures several 2D projections of each clast as it rotates while falling (*Figure 14*), and then uses an algorithm to calculate physical measurements, including length, width, thickness, surface area, volume, and several shape parameters including sphericity, circularity, concavity, and convexity. Samples are run through the PartAn multiple times to minimize errors— for example, from undercounting because of multiple clasts falling in front of one another. PartAn data are used to find the total volume and total surface area of a sample made of tens to tens of thousands of individual clasts, as well as average values for width, length, and shape parameters.



Figure 13: Photograph of MicroTrac PartAn^{3D}

Pumice clasts are placed on the vibrating metal tray (upper right), then fall in front of the camera, which images the clasts as they rotate and fall, recording physical measurements about clast dimensions, volume, surface area, shape, and other parameters.

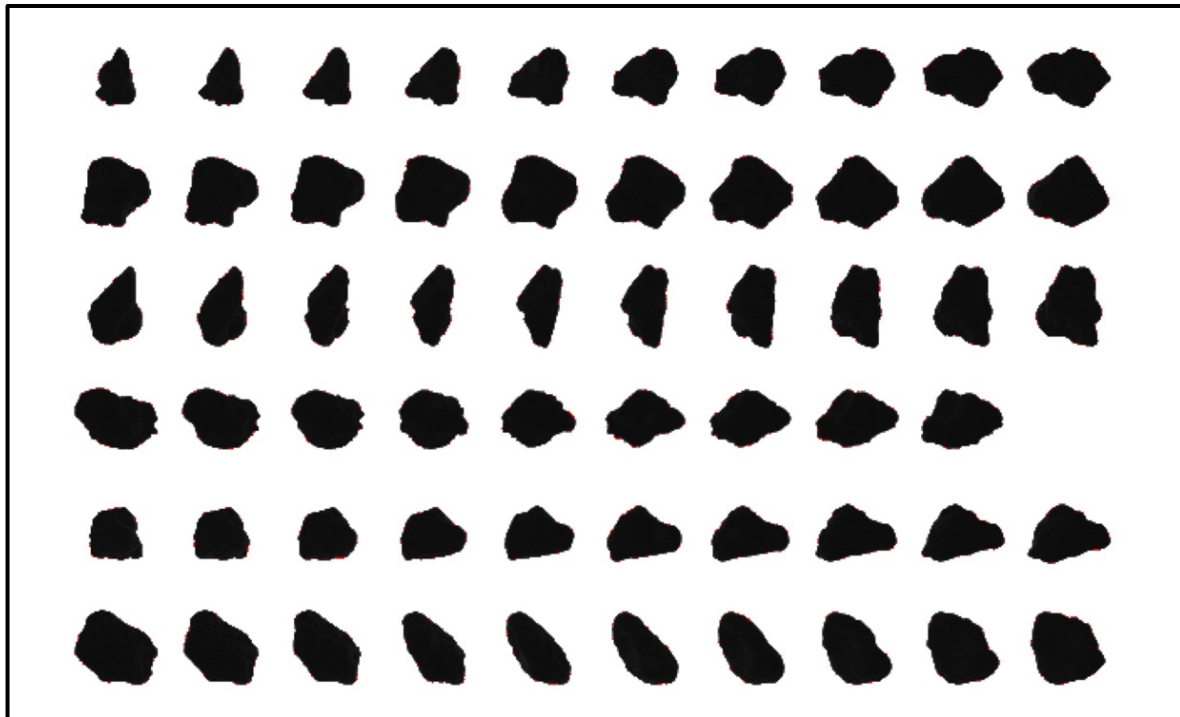


Figure 14: PartAn scans of Mazama Climactic pumices

Each of these 6 rows represents nine to ten 2D projections of the same clast as it falls and rotates in front of the camera.

2C. Helium Pycnometry

Density and porosity (calculations for which are explained below) are derived using data obtained in part using a helium pycnometer. In this procedure, volcanic tephra samples are placed in a chamber calibrated for its volume. The chamber is first evacuated of air by filling it with helium, which has small enough atoms to be able to fill all void space in the chamber: either vesicles within the sample that are connected to the outside or interstitial pore space between individual clasts. The instrument provides the volume of material inaccessible to helium: the volume of solid sample material *plus* the volume of any vesicles within the sample which are isolated (i.e. vesicles surrounded by rock and not connected to the outside of the clast). A subset of the sample is finely crushed to break all isolated vesicles and then re-measured to find the volume of solid material, which is used with the sample mass to calculate the density of the solid phase.

2D. Calculating Packing Fraction and Porosity

Data from the PartAn and helium pycnometry are used to calculate the following:

- *Packing Fraction:*

Packing fraction (*PF*) is a measure of how closely clasts stack together. The packing fraction of a system (*Equation 1*) is the proportion of the space occupied by the clasts as opposed to the interstitial space in between the clasts. Calculating packing fraction requires (1) the bulk volume of a sample (Vol_{bulk}), which is the volume that sample occupies within a container (including interstitial space) and (2) the sum of the external volumes of all the individual clasts constituting the sample ($Vol_{external}$), which are obtained by the PartAn:

Equation 1: Packing Fraction

$$PF = \frac{Vol_{external}}{Vol_{bulk}}$$

- Porosity:

Porosity (ϕ) is a measure of the amount of a clast which is void space. Rocks like pumice, which have lots of vesicles, have a high clast porosity. *Connected porosity* (ϕ_{con}) is the proportion of a clast which is occupied by void space that is connected to the outside of the clast (and accessible to helium). *Isolated porosity* (ϕ_{iso}) is the proportion of the clast which is made of “bubbles” which are completely sealed off by solid material, so are not connected to the outside of the clast (and inaccessible to helium). Lastly, *total porosity* (ϕ_{total}) is the combination of these: the total proportion of the clast which is void space.

The measurements described here calculate the porosity of individual clasts within a sample, and not the bulk porosity of a deposit or other collection of multiple clasts.

Calculating clast porosity of a sample requires several parameters obtained from the PartAn and helium pycnometry and consists of:

1. Calculating density (ρ_{solid}) of the solid phase (*Equation 2*, the rock material of the clast, without any pore space) uses the mass (m_{solid}) and volume of the sample solid phase when crushed (V_{solid}):

Equation 2: Density of solid phase

$$\rho_{solid} \left(\frac{g}{cm^3} \right) = \frac{m_{solid}(g)}{V_{solid}(cm^3)}$$

2. Calculating the volume of isolated pores in the sample (V_{iso} , *Equation 3*) and isolated porosity (ϕ_{iso} , *Equation 4*) uses the combined volume of isolated pores and solid phase as measured by the pycnometer ($V_{combined}$), the volume of the crushed sample also from the pycnometer

(V_{solid}), and the external volume of the sample as measured by the PartAn (V_{ext}):

Equation 3: Volume of isolated pores

$$V_{iso}(cm^3) = V_{combined} - V_{solid}$$

Equation 4: Isolated porosity

$$\phi_{iso} = \frac{V_{iso}}{V_{ext}}$$

3. Calculating the volume of connected pores in the sample (V_{con} , Equation 5) and connected porosity (ϕ_{con} , Equation 6) uses the external volume of the sample (V_{ext}), from the PartAn, and the combined volume of isolated pores and solid phase ($V_{combined}$) from the pycnometer:

Equation 5: Volume of connected pores

$$V_{con} = V_{ext} - V_{combined}$$

Equation 6: Connected porosity

$$\phi_{con} = \frac{V_{con}}{V_{ext}}$$

4. Confirming total porosity (ϕ_{total}) requires the volume of isolated pores (V_{iso}), the volume of connected pores (V_{con}), and the external volume of the sample (V_{ext}):

Equation 7: Total porosity

$$\phi_{total} = \frac{V_{iso} + V_{con}}{V_{ext}}$$

2E. Making Synthetic Graywater

The graywater in these experiments is created using the NSF (National Sanitation Foundation) 350 Challenge graywater mixture (*Table 2*) – a recipe for synthetic graywater that replicates the conditions of real-world wastewater without some of the larger, more logistically-challenging particles typically involved. These excluded materials include food, hair, grease, and sweat, and are left out because they can clog tubing and pump mechanisms while also creating potential biological hazards in our labs, which are not outfitted to deal with such risks. Graywater ingredients are purchased at a grocery store and mixed into lab tap water in a bucket using an electric whisk.

Table 2: NSF 350 Challenge graywater recipe

<i>Graywater Ingredient</i>	<i>Mass (g) / 10 L</i>
<i>Body wash w/ moisturizer</i>	3.0
<i>Liquid hand soap</i>	2.3
<i>Conditioner</i>	2.1
<i>Shampoo</i>	1.9
<i>Bath cleaner</i>	1.0
<i>A2 fine test dust (ISO 12103-1 std.)</i>	1.0
<i>lactic acid</i>	0.3
<i>toothpaste</i>	0.3
<i>deodorant</i>	0.2

2F. Graywater Characterization Methods

Across our different experiments, we measured several chemical and physical parameters in the graywater. Definitions, units, instrumental specifics, measurement procedure, and other information about each of these analytes can be found in *Table 3*. Due to discord between guidance from different regulatory and research bodies, it is challenging to find consistent standards for wastewater effluent. Where possible below, we note standards for drinking water because they are more agreed upon; however, it is important to note that contaminant thresholds for “safe” wastewater effluent are typically considerably higher than those for potable water, and that water can be “clean” and ready for reuse even if it doesn’t meet drinking water standards.

Chemical Oxygen Demand (COD):

COD is a measure of how much oxygen can be consumed in a solution by chemical reactions and reflects the amount of inorganic and organic matter in the water. This metric is particularly useful for understanding the environmental impact of releasing treated wastewater because effluent with a high COD could result in harmful decreases in oxygen in ecosystems downstream. In wastewater treatment, COD is often measured as a supplement to 5-day biochemical oxygen demand (BOD₅), which records matter in the water that can be consumed through biologic reactions and takes five days to complete. Treatment standards vary, but many consider 10-15 mg/L COD to be a permissible amount in municipal wastewater effluent.

We measure COD using Hach tests which require 2 mL of graywater to be piped into a single-use vial that was pre-filled with chemicals. The vial is then placed in a reactor block at 150° C for two hours, after which it cools to room temperature before being analyzed in triplicate using a spectrophotometer to find COD in milligrams per liter (mg/L). COD is measured in our bottle still-water and our column flow experiments.

Conductivity:

Conductivity reflects the ability of water to transmit an electrical current. Water with more dissolved materials like salts and some chemicals has higher conductivity, but temperature can also have an effect (higher temperatures increase conductivity). Lower conductivity is better for water quality, as it means there are fewer contaminants dissolved in the water.

We measure conductivity in our graduated cylinder still-water experiments using a BlueLab handheld probe which is placed in the water for a few seconds before returning a reading in EC (electrical conductivity units).

Dissolved Oxygen (DO):

Dissolved oxygen (DO) measures the amount of oxygen dissolved in water. Water with low DO can result in ecological damage, such as die-offs. “Safe” water should have DO of 6.5 mg/L or higher; there is not an upper limit for safe levels.

We measure DO using a SPER Scientific 850045 handheld dissolved oxygen meter, which needs to be immersed in water and moved continuously side to side for proper results in milligrams per liter (mg/L). DO is measured in our bottle still-water experiments. The instrument is calibrated at the start of each test.

Nutrient Content:

Prior to obtaining the materials and equipment to test for nitrogen, phosphate, chemical oxygen demand, and dissolved oxygen, we used a BlueLab handheld nutrient meter which gave a low-resolution approximation of total nutrient content in milligrams per liter (mg/L). This was used to collect data during our initial graduated cylinder still-water experiments but phased out before later tests and replaced with more precise instruments.

pH:

pH measures the acidity of water, ranging from 0 (acidic) to 14 (alkaline) with 7 being neutral, using the relative proportions of free hydrogen and hydroxyl ions in a sample. pH units are logarithmic—, water with a pH of 4 is ten times more acidic than water with a pH of 5. Typically, safe drinking water has pH ranging from 6.5 – 8.

In our graduated cylinder experiments, we use a handheld BlueLab pH probe; in our bottle and column experiments, we take triplicate readings use a countertop Orion Star A111 meter which has to be immersed in a sample for a few minutes before reporting a reading. The probe is calibrated at the beginning of every lab day using pH 4.0 and 7.0 standards.

Phosphate:

Phosphate (PO_4^{3-}) is a nutrient that can feed harmful algal blooms and other environmentally damaging processes in high concentrations. It is typically measured in milligrams per liter (mg/L). Although standards vary, water levels around 10 mg/L are often considered safe for environmental release.

In our bottle still-water and column experiments, we measure phosphate using Hach single-use tests which require 5 mL of graywater to be piped into a vial which was pre-filled with chemicals. The vial is then placed to rest for ten minutes, after which it is using a spectrophotometer to find triplicate readings of phosphate in milligrams per liter (mg/L). These tests also record two other measures of phosphate levels: $[\text{PO}_4^{3-}\text{-P}]$ and phosphorus pentoxide $[\text{P}_2\text{O}_5]$. However, our results solely report PO_4^{3-} .

Temperature:

We measured temperature for all our experiments in degrees Celsius ($^{\circ}\text{C}$) using a EZ9901 combination TDS-temperature handheld probe. There is no relevant standard for water temperature pertaining to wastewater quality, but temperature can affect other parameters such as dissolved oxygen and pH.

Total Dissolved Solids (TDS):

Total dissolved solids (TDS) is the total amount of solid material dissolved into water. The environmental implications of water with high TDS depend on what the dissolved solids in question are, but general water quality standards suggest a safe level around 500 parts per million (ppm).

We measure TDS during all of our experiments using a EZ9901 combination TDS-temperature handheld probe, which is inserted into a water sample and returns a result in ppm.

Total Nitrogen:

Nitrogen is a nutrient that can feed harmful algal blooms and other environmentally damaging processes in high concentrations. It is typically

measured in milligrams per liter (mg/L). Although standards vary, water levels around 2-6 mg/L are often considered safe for environmental release.

In our bottle still-water and column experiments, we measured total nitrogen using Hach single-use tests which require: (1) the addition of 1.3 mL graywater to 1.3 mL of a provided chemical solution (Solution A) and a tablet of Reagent B in a vial; (2) the placement of the vial in a reactor block at 120° C for 30 minutes; (3) the cooling of the vial to room temperature; (4) the addition of 0.5 mL of the digested sample to a test tube pre-filled with reagent chemicals with 0.2 mL of another provided chemical solution (Solution D); (5) the addition of 1.0 mL of undigested graywater to another test tube with 0.2 mL of Solution D; (6) waiting 15 minutes for an exothermic reaction to occur and then for the test tubes to cool to room temperature; before (7) measuring both test tubes in triplicate using a spectrophotometer. This method also returns data on total nitrate (nitrate plus nitrite) and total Kjeldahl nitrogen.

Turbidity:

Turbidity is a measure of water clarity, which can be decreased by the presence of suspended solids like clays. Cloudy water can be environmentally harmful and have implications for oxygen levels in ecosystems. Turbidity is measured in several ways, including nephelometric turbidity units (NTU), an optical measurement collected by shining a light through water and observing the disturbance of light rays from particles of solids suspended in the water. Lower turbidity creates healthier water; standards vary but levels around 0.15 – 0.30 NTU are considered very safe.

We measure turbidity in all our experiments using a Shanghai Yuefeng SGZ-200BS tabletop turbidity instrument, which requires the filling of a 20 mL bottle with water and placing the bottle inside the instrument before recording the displayed turbidity

level in NTU after 10 seconds. Settling of particles causes turbidity readings to drop after this time. The instrument is calibrated using a 200 NTU standard.

Table 3: Water quality parameters

Water Quality Parameter	Measurement Units	Instrument Used	Acceptable Water Quality Standard	Instrument Minimum/ Maximum values	Instrument Accuracy
Chemical Oxygen Demand (COD)	Milligrams per liter (mg/L)	Hach TNT822 COD tests, reactor block, spectrophotometer	10 –15 mg/L	20 – 1500 mg/L	
Conductivity	Electrical Conductivity Units (EC)	BlueLab Conductivity probe (BP5-2106-01618)	1 EC	0 – 10 EC	0.1 EC
Dissolved Oxygen (DO)	Milligrams per liter (mg/L)	DO probe (SPER Scientific 850045)	6.5 – 8 mg/L	0 – 20 mg/L	0.1 mg/L
Nutrient Content	Parts per million (ppm)	BlueLab Nutrient Content probe			
pH	pH units	Tabletop pH meter (Orion Star A111)	6.5 – 8 pH units	0 – 12 pH units	
Phosphate	Milligrams per liter (mg/L)	Hach TNT846 phosphate tests & spectrophotometer	10 mg/L	1.6 – 30 mg/L	
Temperature	Degrees Celsius	TDS/temperature probe (EZ9901)			0.1 °C
Total Dissolved Solids (TDS)	Parts per million (ppm)	TDS/temperature probe (EZ9901)	500 ppm	1-990 ppm	1 ppm
Total Nitrogen	Milligrams per liter (mg/L)	Hach TNT880 nitrogen tests, reactor block, spectrophotometer	2 – 6 mg/L	0 – 16 mg/L	
Turbidity	Nephelometric Turbidity Units (NTU)	Tabletop turbidity meter (Shanghai Yufeng Instruments)	0.15 – 0.3 NTU	0 – 200 NTU	0.1 NTU

3. PRELIMINARY STILL-WATER EXPERIMENTS

From 2021 through 2024, we conducted a series of experiments testing static (still-water) chemical and physical interactions between graywater and pumice. These composed large parts of both my undergraduate and graduate research projects and laid the foundations for the column filtration work that makes up the majority of this thesis' findings.

3A. GRADUATED CYLINDER STILL-WATER EXPERIMENTS

3A.i. Overview

Previous work on this topic began with my undergraduate honors research thesis, completed for graduation from the UO Clark Honors College and Department of Earth Sciences in Spring 2022. This project investigated interactions between graywater and pumice (and between graywater and scoria, a porous mafic volcanic rock) in still-water systems. We measured water quality parameters in the graywater over seven days while it was in contact with the rocks, mainly focusing on pH, turbidity, and total dissolved solids (TDS), but also collecting data on temperature, nutrient content, and conductivity. This test was repeated with different sizes of rocks to illuminate the effect of changes in physical rock characteristics on trends in the graywater. During this time, we also conducted tests of water absorption into pumices and scoriae of different sizes, hoping to constrain absorptive capacity. These experiments established a baseline for ambient chemical interactions between pumice and scoria and graywater, setting the stage for my master's work to follow. Although data were collected and reported for both scoria and

pumice interactions, this summary only reviews the findings for the pumice experiments. Two pumice samples were used: one from the Climactic and one from the Cleetwood eruption of Mount Mazama. Except where noted, all pumice data are from the Climactic Mazama samples (referred to in my 2022 undergraduate thesis as *PumA*).

[For more detailed descriptions of methods and results from this project, please refer to my undergraduate thesis (*Investigating Graywater Filtration Efficacy of Pacific Northwest Pumice and Scoria*, 2022), available in Scholars' Bank through the University of Oregon.]

3A.ii. Methods

Rock Sample Characterization

Using the methods, instruments, and calculations described in **Section 2**, we divided large batches of pumice and scoria from unsorted field samples into size ranges and measured their mass, volume, porosity, and density. The pumice was collected from the South Chemult Quarry, which sells and distributes rock from the Climactic eruption of Mount Mazama (~7.7 ka), in what is now central Oregon, and from a field sampling location of the earlier Cleetwood Eruption of the same volcano (Wiejaczka & Giachetti, 2022). The scoria was collected from a cinder cone near La Pine, Oregon. Samples were sieved into five size fractions (1-2 mm, 2-4 mm, 4-8 mm, 8-16 mm, 16-32 mm), washed, dried, massed, and photographed. The Cleetwood Eruption samples are referred to in my 2022 undergraduate thesis as *PumB*.

Graywater Creation and Characterization

The graywater used in these experiments was made as described in **Section 2E**. Several chemical and optical parameters were measured in the water, including conductivity, temperature, turbidity, total dissolved solids (TDS), nutrient content, and pH. Our results focus on TDS, turbidity, and pH, as the other parameters were either inconclusive (conductivity) or the instruments used did not have enough resolution to provide meaningful results (nutrient content). Tap water from the Physical Volcanology Lab (Volcanology Hall 221-219) was used to make the graywater.

Experimental Methods

Graywater Experiments

In these experiments, pumice and graywater were placed in a graduated cylinder and left to sit for seven days (*Figure 15*). Periodically, the graywater was poured out into a beaker and tested for the water quality parameters mentioned above– this was done with the initial graywater (prior to contact with pumice), then after 3 hours, 24 hours, 3, 5, and 7 days. Measurements were also collected at the same time in a control graywater sample settling on the countertop without any pumice. These experiments were conducted with the five size ranges of pumice that were sieved from the Mazama pumice samples (**Section 2A**).



Figure 15: Graduated cylinders containing graywater and pumice clasts during still-water graduated cylinder experiments

From left to right: Mazama Cleetwood (PumB) 4-8 mm, Climactic Mazama (PumA) 4-8 mm, Climactic Mazama 8-16 mm, Mazama Cleetwood 8-16 mm. Due to pumice being buoyant in water, the clasts are contained in the graduated cylinders using improvised restraints (circles of coarse metal mesh attached to wooden dowels, then taped to the top of the cylinder).

Absorption Experiments

Although helium, which is used to measure connected porosity, can penetrate all the connected pore space within a clast due to its small atomic size, water molecules are about ten times larger than helium atoms and might be too big to enter some of the smallest apertures in between vesicles. We thus ran experiments to determine how much of the connected pore space in the pumice clasts is accessible by water, as opposed to

helium. These experiments were conducted by adding known volumes of water to beakers of known volumes of pumice of a given size and monitoring how much of the water was absorbed. Comparing the volume of absorbed water to the volume of connected pore space within the clasts, as measured via helium pycnometry, provided an estimate of how much of the clasts' pore space was absorbing water during these experiments. It also provided, by difference, an estimate of the proportion of connected pore space which is composed of bubbles too small or convoluted for water to percolate through.

3A.iii. Results

Graywater Experiment Results

Graywater in these static tests (*Figure 15*) experienced three main trends: increase in total dissolved solids (TDS; *Figure 16*); decrease in turbidity (*Figure 17*); and neutralization of pH (decrease of pH relative to an unusually high initial tap water pH; *Figure 18*). These patterns in turbidity and pH were strongest with smaller pumice (1-2 mm) and weakest with larger pumice (>2 mm), suggesting a relationship between the forces driving these responses in the graywater and the surface area of pumice clasts, which is higher for smaller samples. Because the graywater was not continuously flowing through the pumice but was instead still, we believe that the observed changes in pH, turbidity, and TDS resulted from chemical interactions between the rocks and the graywater, occurring at the surfaces of the pumices— so, small pumices with more surface area experienced more intense changes.

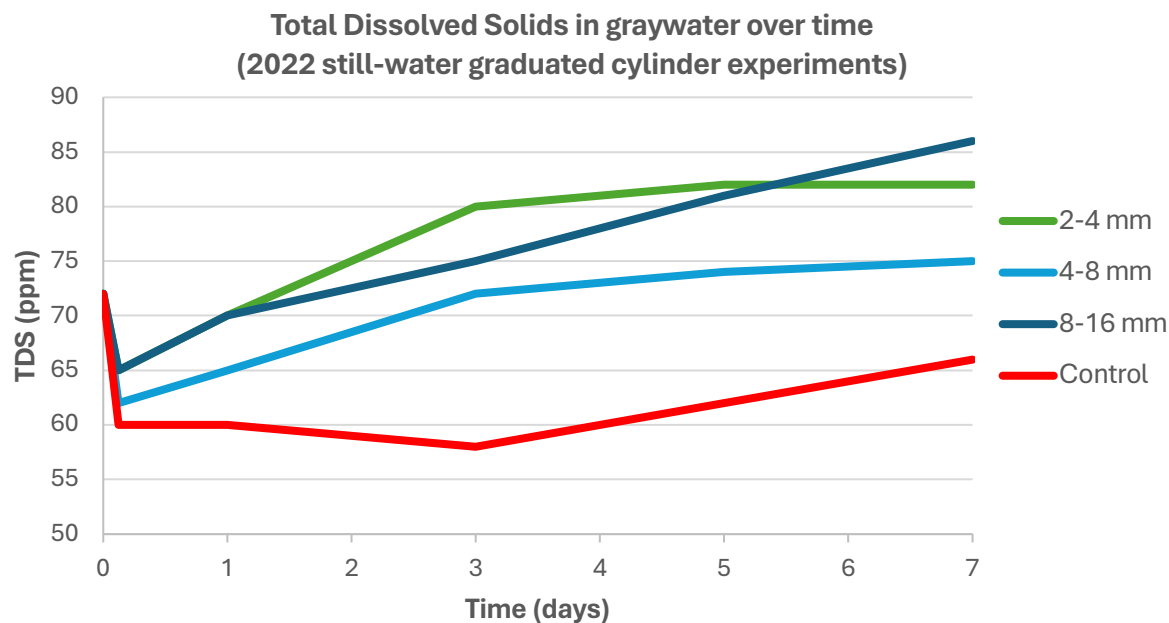


Figure 16: Total Dissolved Solids (TDS) in graywater over seven days, 2022 graduated cylinder still-water experiments

From 2022 undergraduate thesis, Investigating Graywater Filtration Efficacy of Pacific Northwest Pumice and Scoria. TDS (in ppm) drops initially, then gradually increases with time. Graywater in contact with all pumice sizes experiences more TDS increase than the control graywater (red), which loses overall TDS.

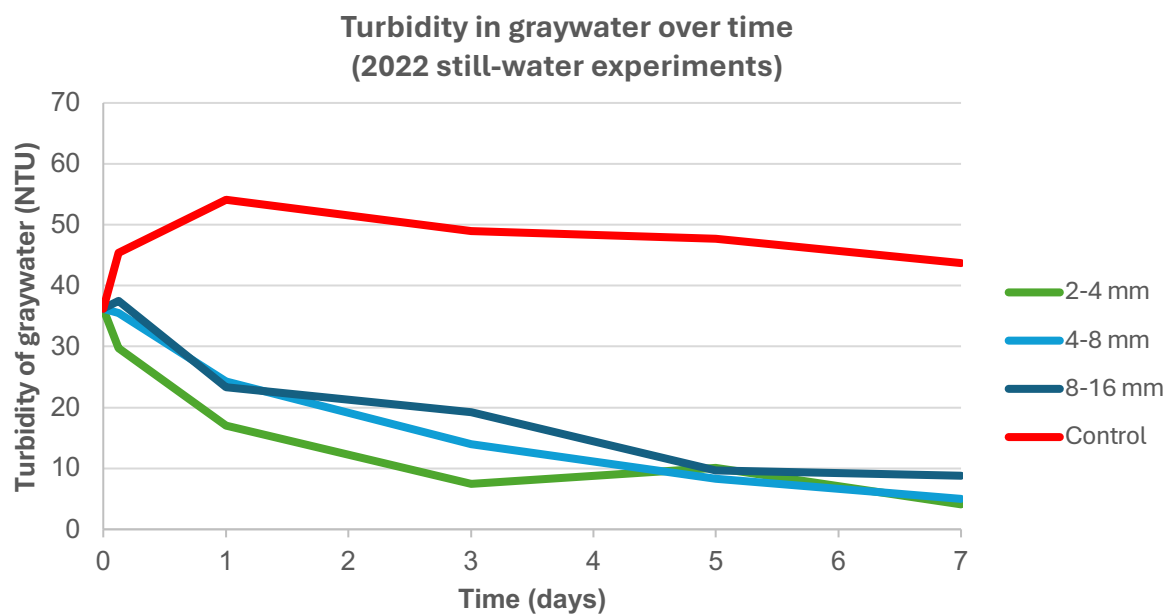


Figure 17: Turbidity in graywater over seven days, 2022 graduated cylinder still-water experiments

From 2022 undergraduate thesis, Investigating Graywater Filtration Efficacy of Pacific Northwest Pumice and Scoria. Turbidity (in NTU) drops in graywater in contact with all pumice sizes, and increases, then plateaus in control graywater (red).

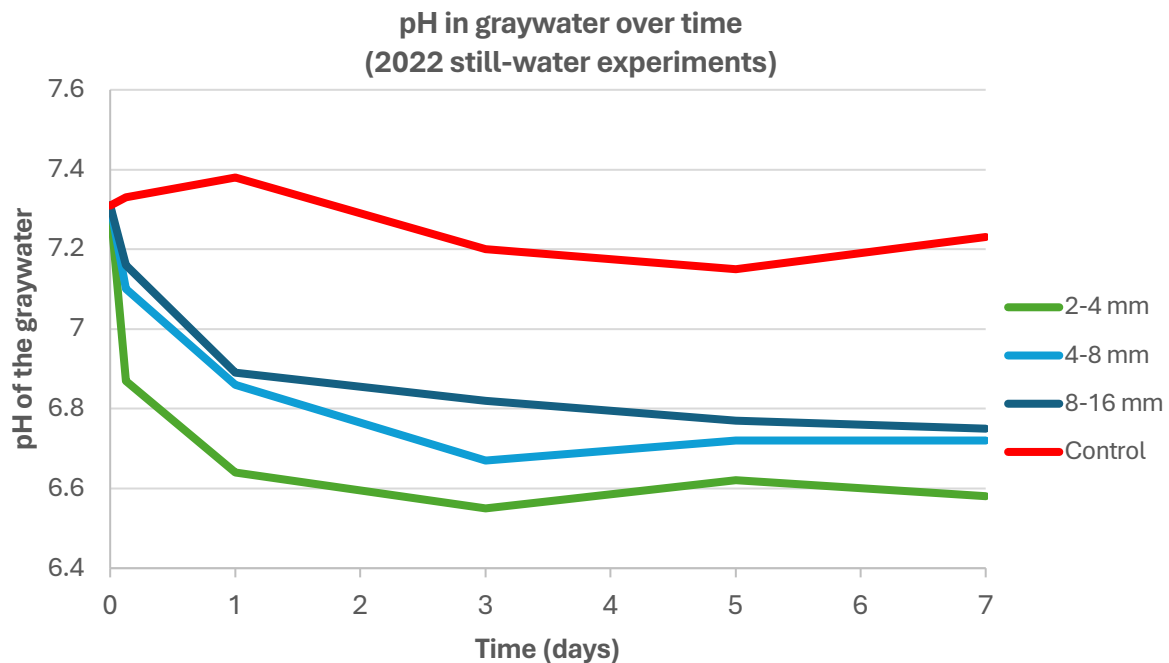


Figure 18: pH in graywater over seven days, 2022 graduated cylinder still-water experiments

From 2022 undergraduate thesis, Investigating Graywater Filtration Efficacy of Pacific Northwest Pumice and Scoria. pH becomes more neutral (dropping from a higher, more alkaline initial amount) in graywater with pumice, and stays relatively constant in control graywater (red).

Interpretation of the data in these experiments is complicated in part by our experimental design: first, the graywater tests were conducted with rock and graywater in graduated cylinders, which made it impossible to collect water samples or use analytical instruments in the containers. As a result, the graywater was poured out into a beaker, sampled, and then poured back into the graduated cylinder. It is possible that this movement of water in and out of the graduated cylinder could lead to brief unintentional filtration, raising the

concern that some of the observed changes to the graywater occurred because of the mechanical and *not* the chemical rock-water interactions as hypothesized.

Absorption Experiment Results

The absorption tests showed that containers full of 1-2 mm, 2-4 mm, and 16-32 mm clasts hold more water than containers with 4-8 mm or 8-16 mm clasts (*Figure 19*). This fluctuation is probably due to a combination of more tightly packed clasts *and* a higher proportion of accessible connected pore space within those clasts. We also found that, upon contact of pumice with water, water absorption into the clasts' connected pore space happens nearly instantaneously.

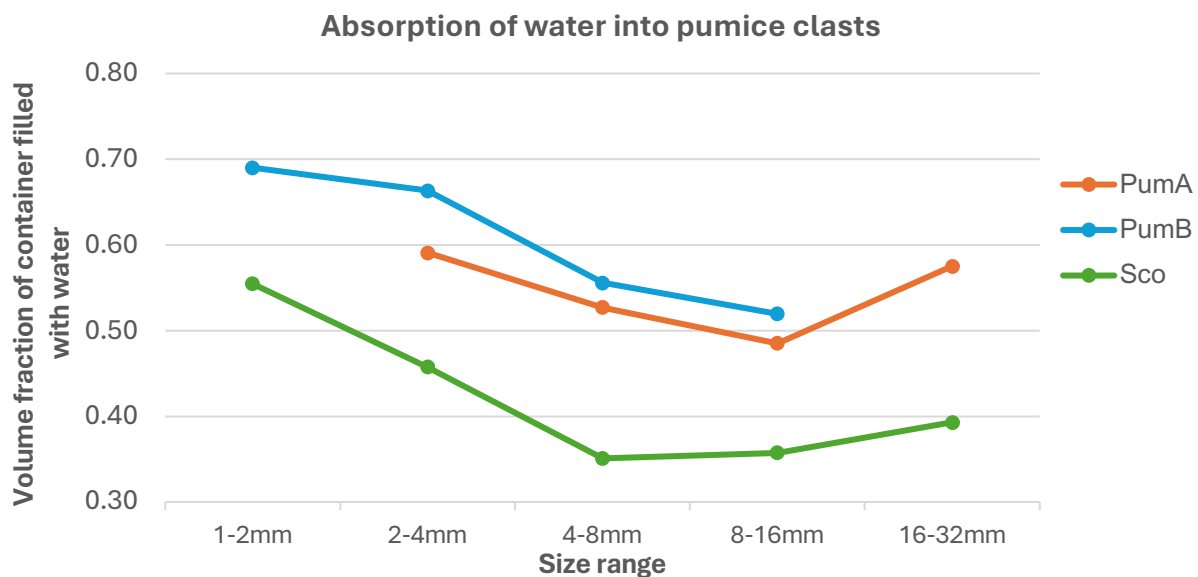


Figure 19: Volume fraction of container filled with water during absorption test

[From 2022 undergraduate thesis, Investigating Graywater Filtration Efficacy of Pacific Northwest Pumice and Scoria. PumA is Mazama Climactic, PumB is Mazama Cleetwood (another eruption of pumice which occurred prior to the ~7.7 ka Climactic eruption, and Sco is Oregon Cascades scoria.)

3A.iv. Conclusions

In summary, the experiments from my undergraduate thesis suggest that smaller pumices, although containing less connected clast porosity than larger sizes, absorb water into more of that connected pore space. This advantage means that systems filled with 1-2 mm clasts hold more water than those filled with larger pumices, with more of that water being stored *within* the internal pore networks, as opposed to *in between* the clasts. This tight packing and higher surface area of the 1-2 mm size fractions is also shown in the graywater interaction tests, in which the highest degree of change in graywater turbidity, TDS, and pH is when the graywater is in contact with the smaller rocks. These results suggest that physical and chemical interactions between the rock and the water occur at both the internal and external surfaces of the pumice, and so the sample with more surface area (1-2 mm) experiences more changes.

3B. BOTTLE STILL-WATER EXPERIMENTS

3B.i. Overview

Further still-water tests were conducted in spring 2023 as early components of my master's research. We placed pumice and graywater in bottles, let them sit, and collected chemical and optical measurements of the water over seven days. These experiments were designed to be a bridge between the static tests of my undergraduate work and the

column-flow tests of my master's work– establishing a more detailed baseline for still-water chemical interactions between graywater and pumice to better contextualize observations from the column experiments.

3B.ii. Methods

Rock Sample Characterization

The pumice used in this experiment was purchased from Lane Forest Products (LFP), a garden and landscaping materials company in Junction City, Oregon. LFP sells pumice from South Chemult Pumice– the quarry from which we sourced the Mazama Climactic samples for our graduated cylinder experiments. The pumice was sieved into 1-2 mm, 2-4 mm, and 4-8 mm size fractions and analyzed using the same procedures as described in **Section 2D**: measurements of mass, density, surface area, volume, external shape parameters, and porosity.

Graywater Creation and Characterization

The graywater used in these experiments was created using the same NSF 350 Challenge procedure described in **Section 2E**. Unlike the prior experiments, the bottle tests were conducted in the Soil & Environmental Chemistry laboratory at the UO (Pacific Hall 210); the tap water we used to create the graywater was from the lab sink. We measured temperature, turbidity, total dissolved solids (TDS), dissolved oxygen (DO), pH, phosphate, total nitrogen, and chemical oxygen demand (COD) in the graywater.

Experimental Methods

For each pumice size fraction, 80 grams of pumice were placed in a 500 mL plastic bottle and 200 mL of graywater were poured into the bottle (*Figure 20*). There were three bottles of each size of pumice, as well as three bottles of control graywater without pumice to establish a robust baseline for graywater change over the experimental period. After the initial graywater was measured, we took further readings at 12-hour, 24-hour, 4-day, and 7-day intervals.



Figure 20: Photograph of still-water bottle experiments

Bottles of (left to right) control graywater and graywater with 1-2 mm, 2-4 mm, and 4-8 mm pumice. Dissolved oxygen, turbidity, total dissolved solids, pH, total nitrogen, phosphate, and chemical oxygen demand were measured in graywater over seven days of static interaction with the pumice.

3B.iii. Results

These bottle experiments showed that static contact with pumice can generate notable changes in graywater chemistry, whereas control graywater without pumice experienced little change. These results are consistent with those of my undergraduate thesis in 2022.

Dissolved Oxygen:

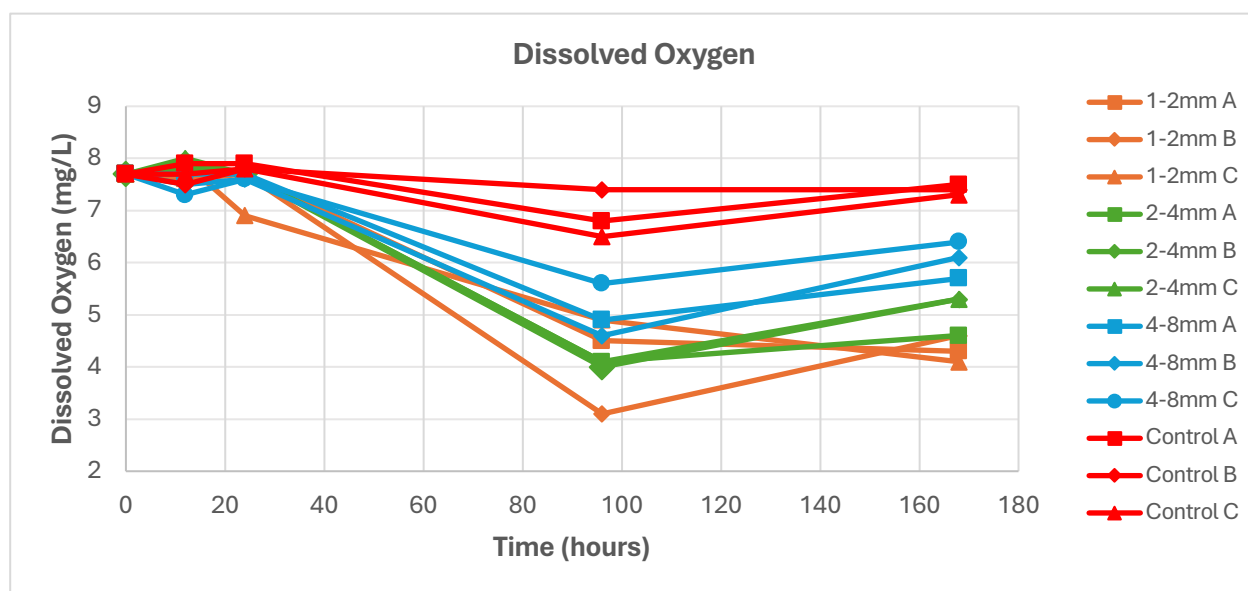


Figure 21: Dissolved oxygen in graywater over seven days, 2023 bottle still-water experiments

Dissolved oxygen (DO) in graywater in bottles with pumice decreases, with the largest drop occurring with 1-2 mm size pumice. Control graywater (red) without pumice experiences little change in DO. A, B, and C labels denote triplicate samples of each size fraction— three different bottles of graywater in contact with the same size of rock.

Compared to the control graywater, which lost <0.5 mg/L dissolved oxygen (DO) on average, all pumice samples experienced much higher decreases in DO (*Figure 21*). The largest decrease (average -3.37 mg/L) was in graywater in contact with 1-2 mm pumices, while the smallest decrease (average -1.64 mg/L) was with 4-8 mm pumices.

We have reason for slight skepticism of our measurements of dissolved oxygen: unlike the other water quality parameters, which were sampled by pouring out a small amount of graywater into a beaker and using that sample in countertop instruments, DO was measured by inserting the handheld DO meter into the graywater within the bottle of pumice. However, due to (1) pumice flotation, (2) absorption of graywater into the clasts, and (3) a decrease in graywater volume in the bottle over time due to graywater sampling to run the other tests, there was not enough graywater standing in the bottle over the top of the pumices to collect accurate readings in the final few days of the experiment. Instead, the DO meter had to be inserted into the graywater in between the clasts, pushing through numerous grains. We believe that a combination of imperfect measurement conditions (wedged in between the clasts, the meter is stuck, while it is supposed to measure while slowly being moved side to side) and damage to the DO meter's sensors from the sharp volcanic glass surfaces of the pumices compromised the readings we collected, especially around the final two 4- and 7-day measurement intervals.

Total Dissolved Solids:

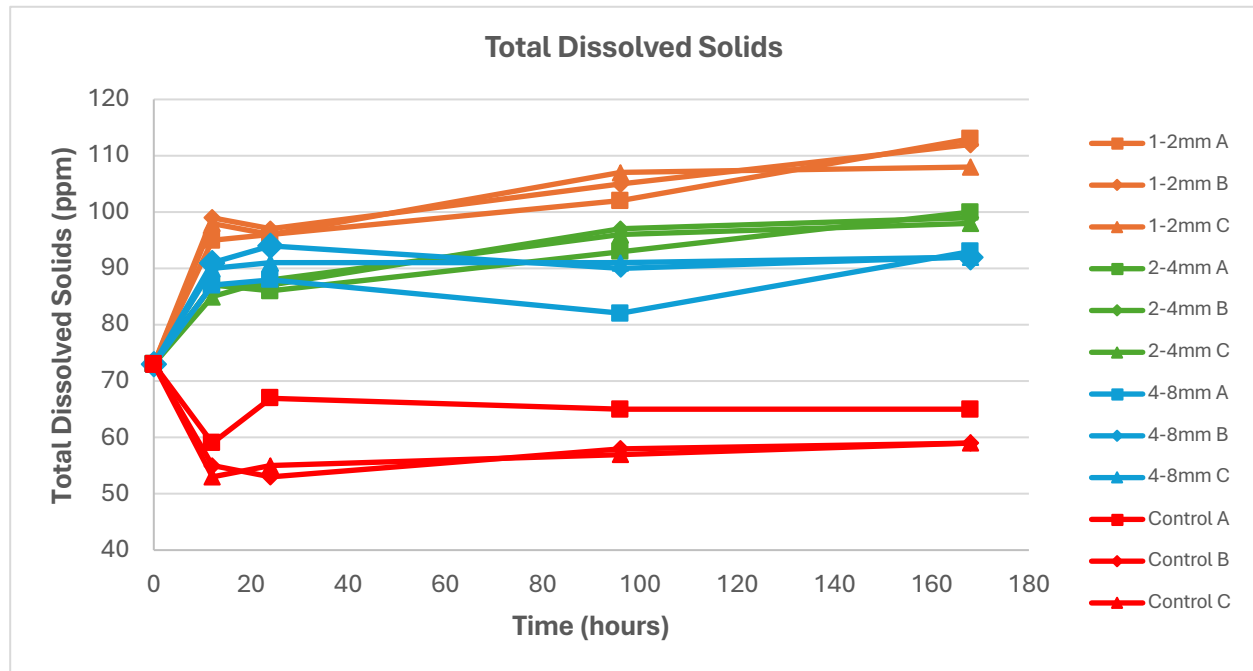


Figure 22: Total dissolved solids in graywater over seven days, 2023 still-water bottle experiments

Total dissolved solids (TDS) in graywater with pumice increases significantly, with the largest increase occurring in graywater with the smallest, 1-2 mm, pumice. Control graywater (red) TDS decreases, then plateaus. A, B, and C labels denote triplicate samples of each size fraction— three different bottles of graywater in contact with the same size of rock.

Relative to the control, graywater in pumice bottles showed increases in total dissolved solids (TDS), with the control losing 12 parts per million (ppm) and the pumice-contact graywater gaining between 19.3 - 38 ppm (Figure 22).

Phosphate:

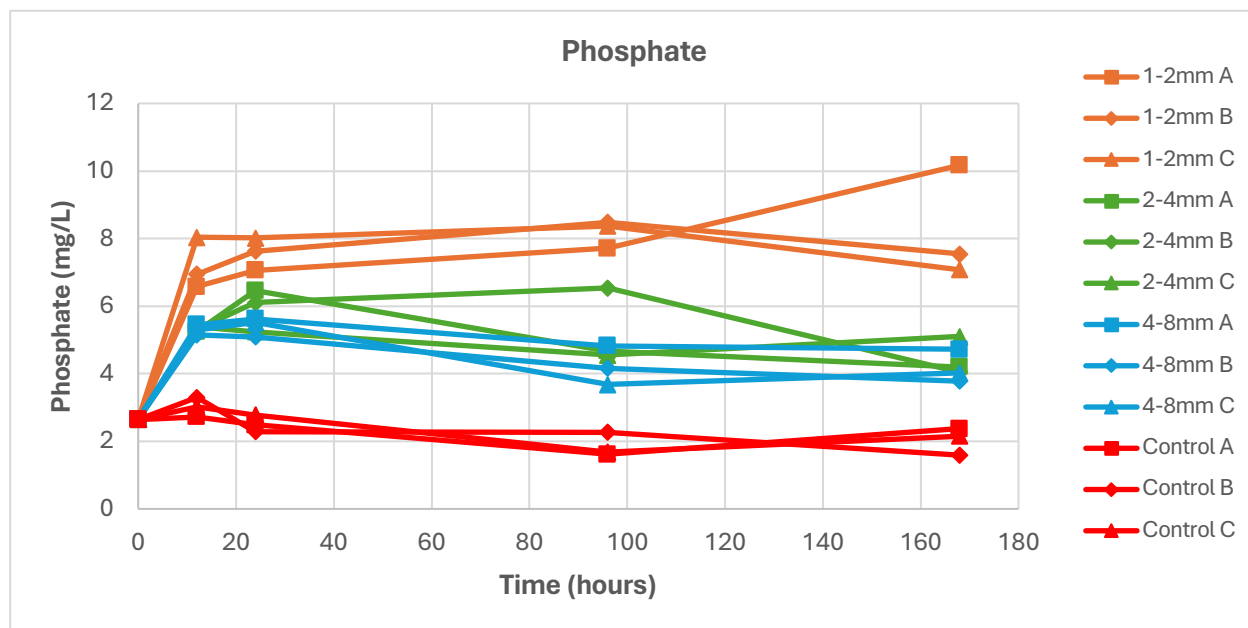


Figure 23: Phosphate in graywater over seven days, 2023 still-water bottle experiments

Phosphate concentration increases rapidly in the first 12 hours graywater in bottles with pumice, with the most dramatic increase in graywater with 1-2 mm pumice. Phosphate in control graywater (red) stays constant throughout the experiment. A, B, and C labels denote triplicate samples of each size fraction– three different bottles of graywater in contact with the same size of rock.

Similarly to TDS, the pattern of increase was observed with phosphate readings, as the control lost on average 0.81 mg/L, but the pumice-contact graywater gained 1.52 - 5.61 mg/L (Figure 23).

Other Parameters (COD, total nitrogen, pH, and turbidity):

Both the control graywater and the pumice-contact graywater experienced decreases in chemical oxygen demand (COD), with the control decreasing by 80 mg/L and the pumice-contact graywater decreasing by 41.33-131 mg/L. Some samples (2-4 mm, 4-8 mm, and control) experienced a decrease in nitrogen of 1.08 and 0.63 mg/L, whereas the graywater with 1-2 mm pumices exhibited an increase in nitrogen of 0.38 mg/L.

pH was neutralized in the graywater in contact with pumice, rising from mildly acidic (~5.5) to relatively neutral (~6.5) in pumice systems. This is an expected result– in the experiments conducted during my undergraduate thesis, graywater that was distinctly basic was neutralized when in contact with pumice as well.

Pumice dust, created via pumice clast abrasion, added to the graywater's preexisting turbidity, causing effluent turbidity values to skyrocket above what could be measured by our turbidity meter.

Time series of COD, nitrogen, and pH in the bottle still-water experiments are in **Appendix IV**.

The most compelling results from these experiments are those related to dissolved oxygen (DO), phosphate, and total dissolved solids (TDS), where variations with time in the graywater in contact with the pumice is far greater than within the control. The greatest amount of change in all three parameters was observed in graywater in contact with the finest (1-2 mm) pumices, whereas the lowest amount of change was with the coarsest (4-8 mm pumice). This trend mirrors the results of the graduated cylinder experiments, which also showed the highest degree of change in the graywater in contact with the smallest clasts.

3B.iv. Conclusions

Consistent with the experiments conducted during my undergraduate thesis, our 2023 bottle graywater experiments demonstrated two major takeaways: (1) in still-water settings, graywater interacts with the pumice clasts, which alters the chemistry of the graywater;

and (2) more changes to the graywater happen when in contact with smaller clasts. This pattern suggests that the processes altering the graywater occur at the interface between the pumice clasts and the surrounding water— meaning that smaller rocks, which have overall higher surface area, create more change.

The observed increases in phosphate and total dissolved solids suggest that small amounts of material from the pumice surfaces (*or* the surfaces of ash fragments resulting from clast abrasion) are being dissolved into the graywater. These results imply that similar interactions could possibly be occurring during filtration of graywater by a pumice filtration system (i.e. where water is flowing through the system). More detailed analyses of precisely *what* materials were causing the increase in graywater phosphate and TDS were not conducted; however, if those materials could produce negative environmental impacts when released in “treated” wastewater, it could pose risks for the real-world application of pumice as a graywater filter.

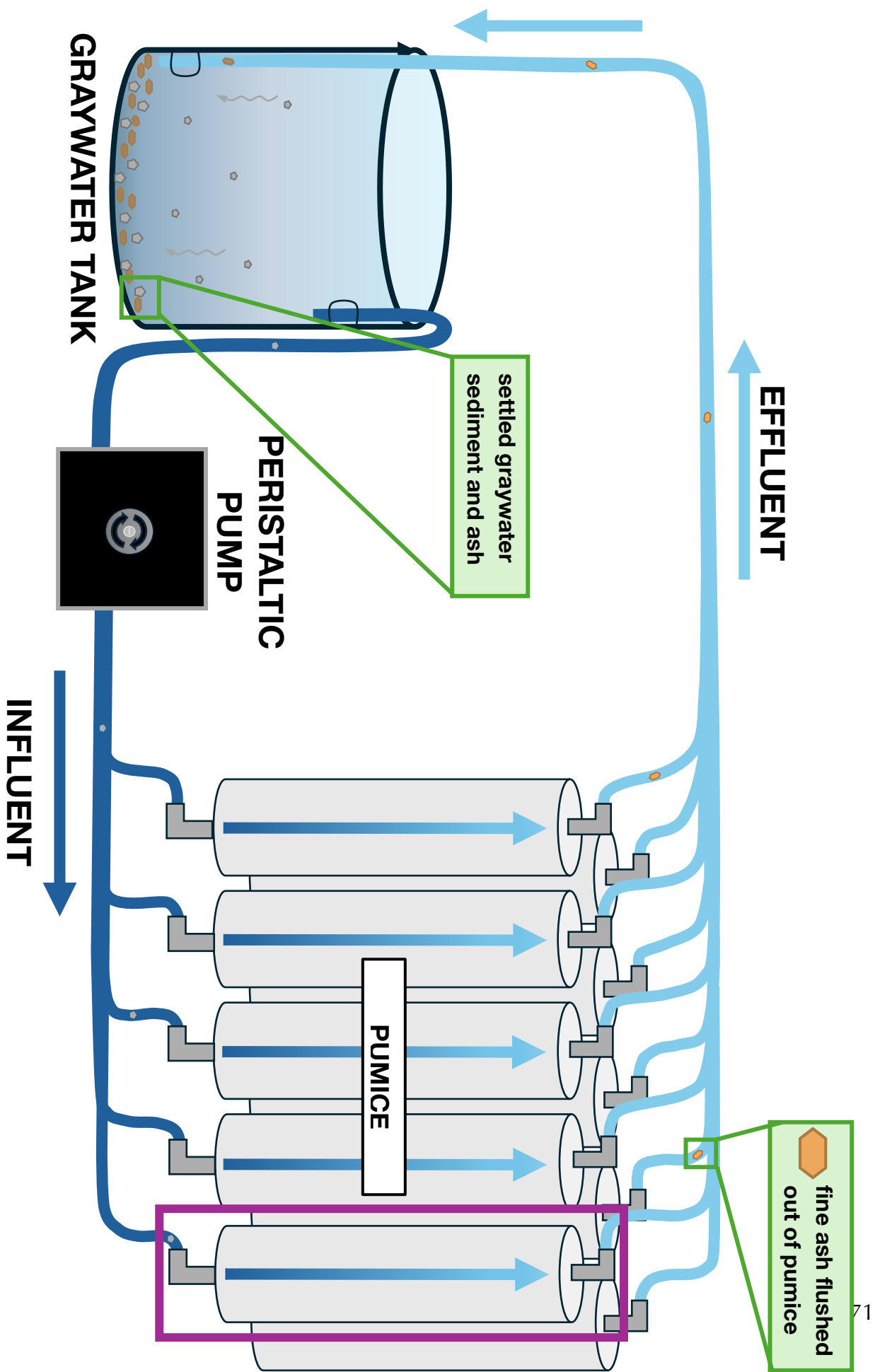
As such, it is crucial to learn whether these same chemical interactions also take place when water is flowing through a setup more akin to real-world graywater filtration systems. We designed the following column filtration experiments to examine the interactions between pumice and graywater in even further depth.

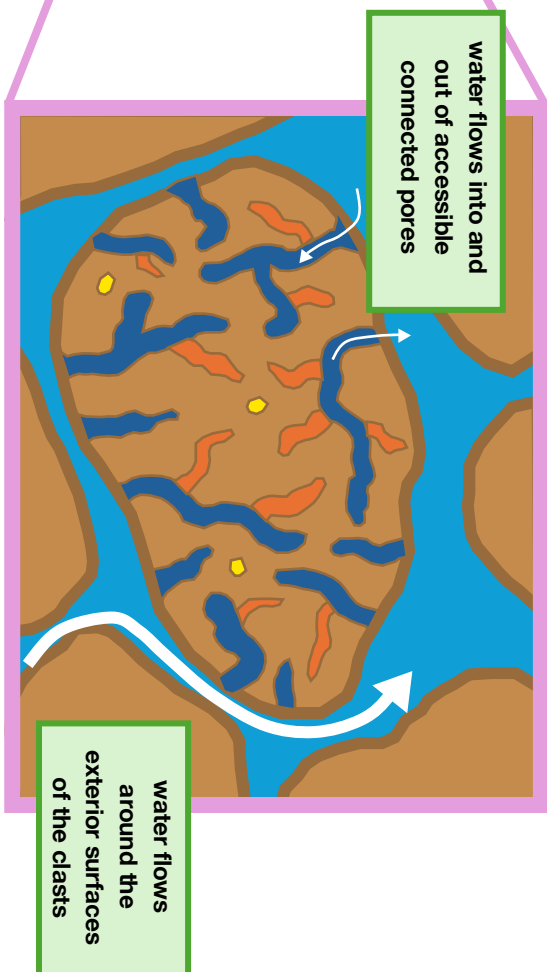
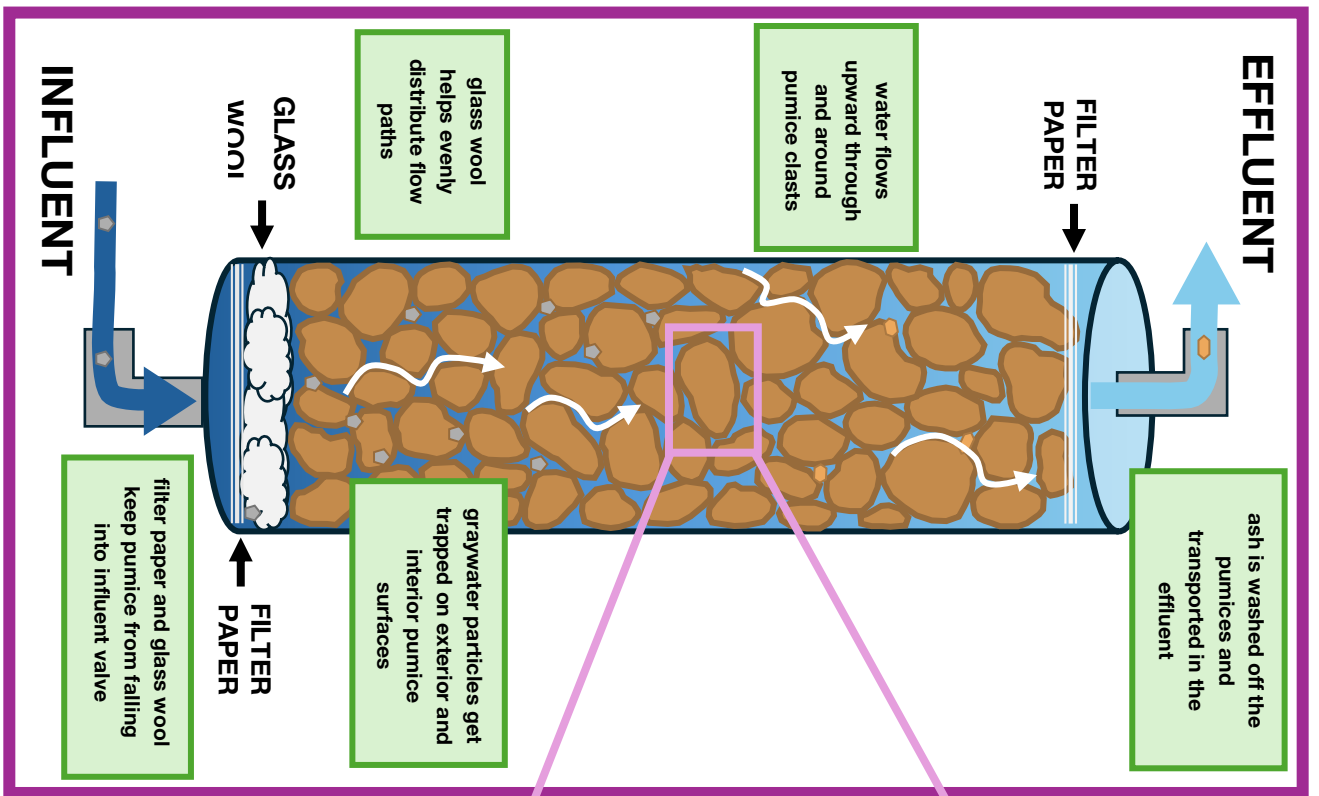
4. COLUMN FILTRATION EXPERIMENTS

4A. Overview

Column filtration is one of the primary methods used in the literature for filtering wastewater. Our preliminary results, which recorded changes to graywater chemistry during still-water contact with pumice, suggest that meaningful interactions occur between the two which may have implications for pumice's use as a graywater filtration material. We designed experiments to test whether these interactions observed in still-water conditions also occur during dynamic column flow, investigate the role of pumice size in graywater interactions, and to better understand the feasibility of a pumice graywater filtration system.

In these experiments, we used a peristaltic pump to continuously cycle synthetic graywater for seven days through ten columns filled with pumice (*Figure 24*). We repeated the test using 5 size ranges of pumice: 1-2 mm, 2-4 mm, 4-8 mm, 8-16 mm, and a mix of 1-16 mm, all from the Climactic Mazama eruption and sampled from the South Chemult Pumice Quarry (*Figure 25*).





Water-accessible connected pores	Connected pore space within the rock that can be reached by water during flow
Water-inaccessible connected pores	Connected pore does not store water during flow due to being too small or tortuous for water to reach
Isolated pores	Pore space sealed off from the outside
Interstitial space	Void space in between pumice clasts

Figure 24: Column system schematic

Using these experiments, we address four main questions:

1. Do the observed interactions between pumice and graywater in still-water conditions occur also in these column filtration systems?

Our preliminary experiments demonstrate that the pumice contributes material to the graywater. We observed increases in dissolved oxygen, total dissolved solids (TDS), and phosphate in graywater, with the largest increases occurring during interaction with the smallest rocks. We surmise this is due to dissolution of pumice at the rock-water interface, which there is more of in smaller sizes of pumice. As the addition of new material to filtered graywater could carry environmental implications for effluent release, it is important for us to confirm whether these interactions also occur during column flow, when water is moving.

2. Does our pumice column filtration system effectively clean graywater?

The ability of a wastewater filtration system to efficiently remove contaminants is imperative. This project compares the amount of contaminant removal from graywater over seven days by different sizes of pumice in vertical columns and contextualizes said removal against relevant water quality standards. We interpret graywater chemistry time series and data on physical characteristics of pumice to understand where in the filtration system contaminant removal is occurring– whether on the walls of pores within the clasts *or* on the exterior grain surfaces in the interstitial spaces between clasts, or both. These

results inform whether pumice could realistically be implemented as a graywater filter in a real-world setting outside the laboratory.

3. How is filtration efficacy influenced by pumice size and why?

Testing graywater filtration with a range of pumice sizes allows us to investigate the impact that physical characteristics of the rock have on their use as filter material. We compare measurements like packing fraction and porosity across the pumice size fractions to trends in graywater chemistry to understand how clast and column structure contribute to filtration efficacy. We also examine differences in flow rate between pumice sizes and their implications for flow paths of water within the columns. These data are important for understanding whether some sizes of pumice are more effective or not and why, allowing future implementation of more efficient graywater treatment systems.

4. How does pumice compare to other natural graywater filters?

By comparing the demonstrated efficacy of pumice as a graywater filter to other materials used in the literature, we can better contextualize our experimental results. This information informs whether pumice is a worthwhile graywater filter, or whether other natural materials are preferable. We also compare the methods utilized in this study to those used for other materials and propose future experiments to further investigate the application of pumice in graywater treatment.

4B. Methods

4B.i. Rock Sample Characterization

Using the standard pumice characterization procedures described in **Section 2A-D**, we sieved and analyzed samples of the Climactic Mazama eruption into four size ranges (1-2 mm, 2-4 mm, 4-8 mm, 8-16 mm; *Figure 25*), then created an additional “mixed” size range by combining equal volumes of each of the four size fractions (*Figure 26*). The samples used were collected from the South Chemult Pumice Quarry (SCPQ) and from Lane Forest Products (which sells pumice sourced from SCPQ). In addition to the analyses performed in our lab and listed in **Section 2A-D**, we sent samples of the four size ranges of Climactic Mazama pumice for mercury porosimetry analysis, which gave us data on the size distribution of the pores and the tortuosity of the pore networks within the pumice clasts, among other things.

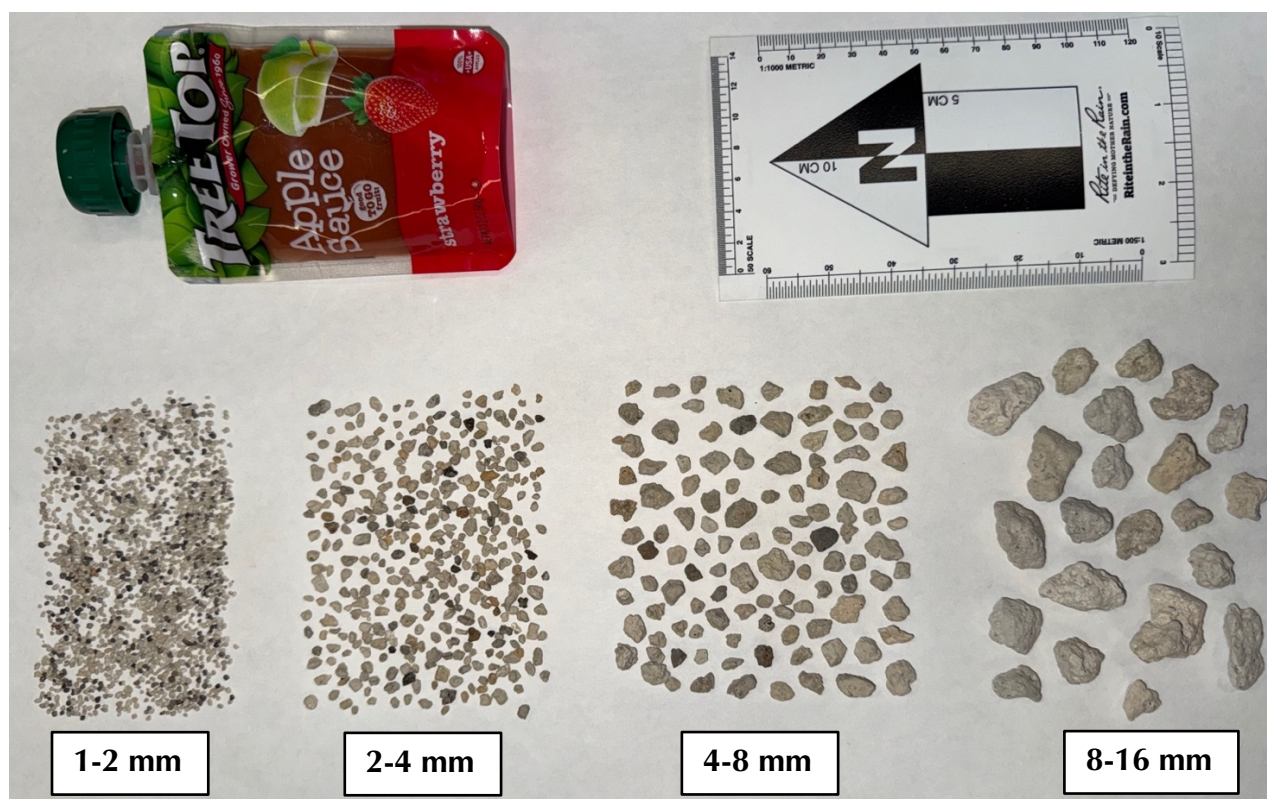


Figure 25: Four sieved sizes of Mazama Climactic pumice used in 2024 column experiments
 Applesauce (an essential field food, crucial to my scientific process) and ruler card for scale.



Figure 26: Mixed size fraction of Mazama Climactic pumice

Our mixed size fraction is composed of, by volume, equal parts 1-2 mm, 2-4 mm, 4-8 mm, and 8-16 mm Mazama Climactic pumice. Applesauce and ruler card for scale.

When characterizing our pumice samples, we also conducted experiments to test the amount of water that could be stored within the clasts through absorption. In these tests, we saturated 400 mL of pumice clasts (approximately the volume of one column) with tap water and measured the change in mass between the dry and wet rock to obtain the amount of water absorbed; we then repeated this test with all five size ranges. Here we assumed that the density of tap water is 1 gram per cubic centimeter.

4B.ii. Graywater Creation and Characterization

The graywater in these experiments was created using the NSF 350 Challenge graywater recipe described previously. Like the bottle experiments, these tests were conducted in the Polizzotto Soil & Environmental Chemistry Lab and the graywater was made using tap water from the laboratory sink. When creating the graywater, we added potassium bromide (KBr) as a conservative tracer. Because we believe the dissolved oxygen (DO) meter was damaged during the bottle still-water experiments (**Section 3B**), we did not collect DO data during the column experiments. We measured turbidity, temperature, total dissolved solids (TDS), pH, total nitrogen, phosphate, and chemical oxygen demand in the lab following the procedures described in **Section 2F** and collected samples to be tested for the bromide tracer by inductively coupled plasma optical emission spectroscopy (ICP-OES) at Oregon State University in Corvallis. For each bromide tracer test, an 8 mL sample was collected and then preserved using nitric acid before being refrigerated. Once

the pilot test, 1-2 mm, 2-4 mm, control, and 4-8 mm experiments had been completed, we transported all the samples to the Keck lab at OSU and performed the analyses there.

4B.iii. Experimental Methods

Our pumice graywater column filtration experiments (*Figure 27*) consisted of ten plastic 400 mL cylindrical columns (21 cm long, 5.5 cm diameter), with filter paper and glass wool at the base, filled with pumice clasts and connected to a bucket using vinyl tubing. The influent tubing (flowing into the columns) was anchored a few centimeters below the top of the bucket and connected to a peristaltic pump rotating at around 80 rotations per minute (RPM). This pump velocity was chosen to be the most comparable to other flow rates used in the literature (e.g. Farizoglu et al., 2004).

Influent tubing was connected to the column base, and water flowed upward through the columns, then out the top of the column as effluent and back to the bucket using more silicone tubing, anchored at the bottom of the bucket (*Figure 24*). Using upward flow, as opposed to downward, allowed us to better constrain flow rate. We chose to anchor the effluent tubing at the bottom of the bucket so that ash and graywater sediment coming out of the columns could more quickly settle gravitationally without being pulled back into the influent tubing. This design detail replicates the settling tanks which are common components of graywater filtration systems (e.g., Tusiime et al., 2022; Albalawneh et al., 2017).

Before the experiment, a circle of filter paper was added loosely to the bottom of the column. This was not for filtering the graywater, but for preventing pumice clasts from falling through the influent valve and into the tubing. On top of the filter paper was a small layer of compressed glass wool, which was packed down to disperse flow paths laterally across the width of the column and further prevent pumice settling out of the column through the valve at the base (since the diameter of the valve is 5 mm, this is particularly problematic for the 1-2 mm, 2-4 mm, and mixed pumice size fractions). Dry pumice was added to the columns, then another circle of filter paper was placed on top before the lid was sealed on with vacuum grease to prevent leakage.

Pilot trials of the column system throughout spring and summer 2024 experienced considerable setbacks with leaking seals at the top and base of the columns. After several failed trials, we discovered that the O-rings we had been using at the top of the columns were faulty and creating leaks. The issue was rectified by purchasing new O-rings and sealing the columns with additional vacuum grease. Prior to the addition of the glass wool, early trials also encountered pumice clasts falling through the valve after moving around the filter paper (which was floated upward by influent water) and sinking into the influent tubing before reaching the peristaltic pump and puncturing the peristaltic tubing segment.



Figure 27: Photograph of 2024 column flow experiments

Graywater flows out of the bucket on the left, through the tubing and through the peristaltic pump, then continues upward into the columns. The combination of glass wool and filter paper at the base prevents pumice falling into the influent tubing and disperse flow paths of water laterally across the column. Effluent graywater leaves the columns through the lid and upper valve and then flows back into the bucket, where sediment and ash settle out and the graywater then cycles back into the columns.

The day prior to the start of each filtration experiment, we attached the influent tubing to a tank of deionized (DI) water and pumped the DI water through the pumices for up to six hours to flush fine ash fragments off the rocks. By collecting sediment settled out of the effluent from this procedure, we observed that this DI flush also removed small (tens of microns long) fibers of glass wool from the columns (Figure 28). During this flow

procedure, we also measured the flow rate (Q) of the entire system by tracking the amount of time (T) it took the system to pump one liter of water. We repeated this measurement four to five times (T_1 through T_4) and then calculated the flow rate as an average (*Equation 8*). Following the flush procedure, we disconnected the influent tubing from the pump and draped the tubes over the edge of the lab countertop so that water could drip out of the columns into a tray below, then left it overnight.

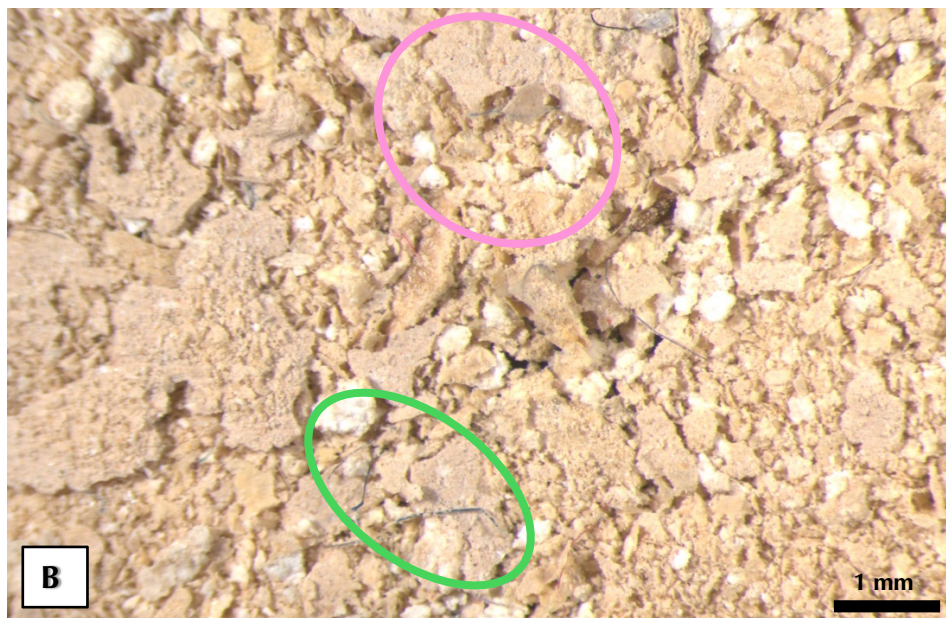
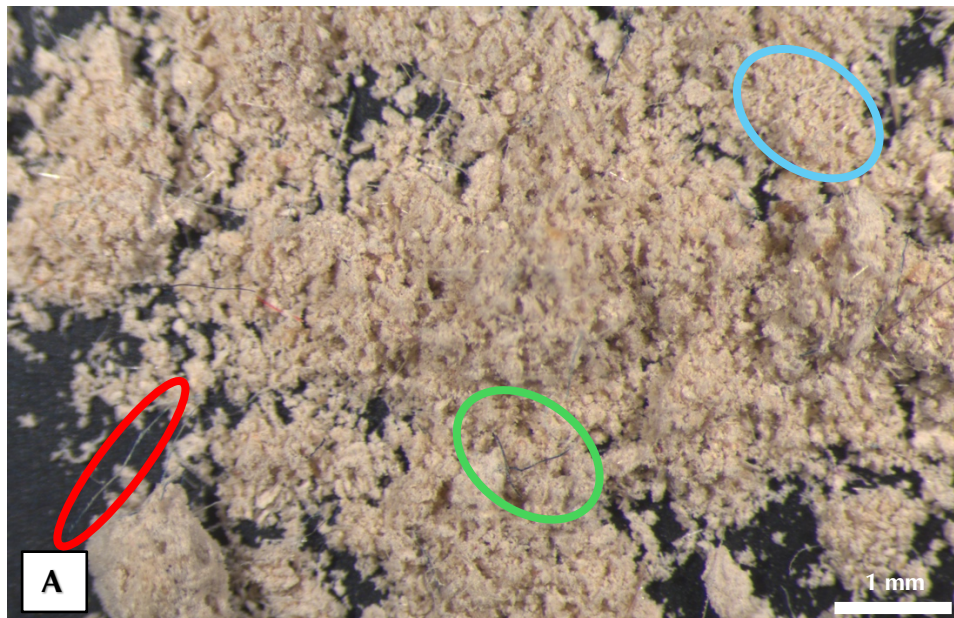
Equation 8: Flow rate, liters per hour

$$Q\left(\frac{L}{hr}\right) = \frac{1L}{\frac{(T_1 + T_2 + T_3 + T_4)}{4}}$$

On the first day of each filtration experiment, we made 8 liters of graywater using the recipe described in **Section 2E** and reconnected all tubing to the bucket as shown in (*Figure 24*) and (*Figure 25*). We then took an initial sample of the graywater to test for the water quality parameters listed in **Section 4B.ii** before starting the pump. We took further samples of the graywater for measurement after 30 minutes, 1 hour, 12 hours, 24 hours, 48 hours, 4 days (96 hours), and 7 days (168 hours). Each measurement was conducted in triplicates to ensure accuracy. We collected sediment that settled out of the graywater at the base of the tank to be analyzed under a microscope (*Figure 28*).

Each experiment thus consisted of eight days (one flush day followed by seven days of column flow) and this process was repeated for all five pumice sizes. During this time, we also ran three separate control experiments in which a liter of graywater in a beaker was left on the counter to settle naturally and measured for the same parameters at the same time intervals as the graywater flowing through the pumice columns. One of these

graywater control experiments included a mechanical stir bar which was constantly rotating over the seven days to test the impact of agitation on the graywater quality over time; the other two controls did not include a stir bar. We also collected settled sediment from the bottom of the control experiment beakers (*Figure 28*).



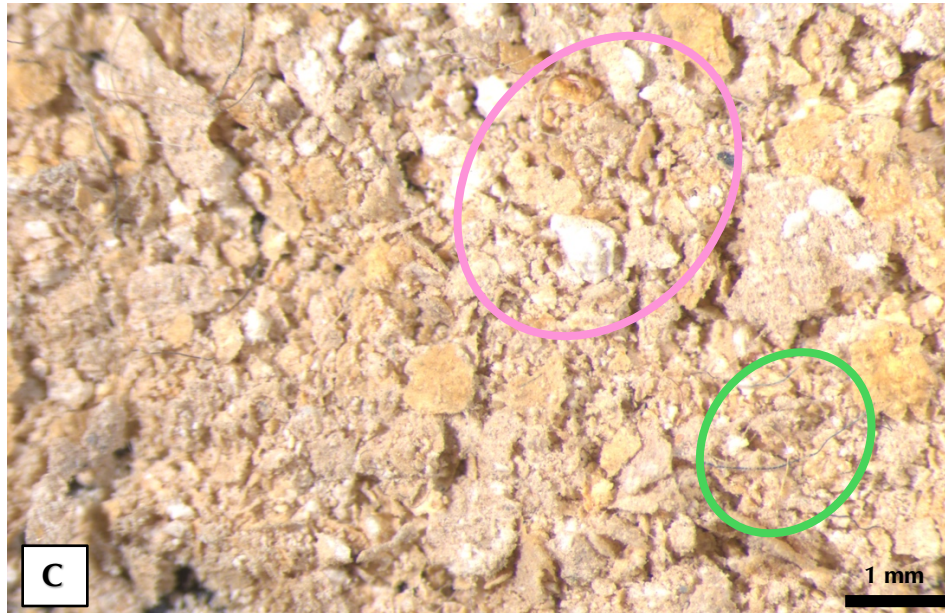


Figure 28: Sediment settled out of flush system, control graywater, and graywater tank during column flow.

- (A) In our flush procedure, we flowed deionized (DI) water through the pumice columns for several hours to remove ambient fine ash from the surfaces of the clasts. The sediment that settled out of the effluent from this procedure was dried and imaged using a microscope. This sediment contains multicolored fibers, presumably from clothing, storage, or other anthropogenic contamination following collection (circled in green), straight clear fibers (circled in red), presumably fragments of the brittle glass wool used to pack the column base, and fine ash particles (tens of microns in size, circled in blue) which attached statically to these fibers. The white scale bar in the photograph is 1 mm long.
- (B) The sediment that settled out of the control graywater beaker also contains multicolored fibers (circled in green), as well as abundant fine tan, gray, and white particles that cemented into cohesive layers at the bottom of the beaker (circled in pink). These layers broke into small flat pieces when removed from the beaker. The black scale bar in the photograph is 1 mm long.
- (C) The sediment that settled out of the graywater tank during column flow also contains multicolored fibers (circled in green) and cemented into flat layers at the bottom of the tank, which broke similarly to the layers in the control graywater beaker. The tank sediment contains tan, brown, yellowish, white, and gray grains (circled in pink) of different sizes ranging from tens of microns to millimeters in scale, with more fine material than the control graywater sediment. The black scale bar in the photograph is 1 mm long.

4C. Results

4C.i. Pumice Characterization

Pumice physical characteristics are provided in *Table 4*. Surface area is highest in the 1-2 mm size fraction, which has an external surface area of 11,168 cm², an external volume of 294 cm³, and a packing fraction of 74%. The 2-4 mm and 4-8 mm size ranges have different amounts of external surface area (5,157 and 2,848 cm²), but overall similar external volumes (290 and 295 cm³) and packing fractions like each other and to 1-2 mm samples (73% and 74%). 8-16 mm pumice packs much less tightly (53%) than the other size fractions, with a similar external volume to the 2-4 mm and 4-8 mm sizes (210 cm³) but lower surface area (844 cm²). The mixed size, which was composed of equal parts by volume of each of the four size fractions, had traits which reflected this range of sizes: external volume of 309 cm³, external surface area of 4412 cm², and packing fraction of 77%.

Our componentry test showed that the 1-2 mm pumice is 81% pumice and 19% lithics (dense rock material which is not pumice).

Table 4: Physical characteristics of pumice size fractions, measured using a 400 mL bulk sample

	1-2 mm	2-4 mm	4-8 mm	8-16 mm	mixed
dry mass (400 mL) [g]	216.4	146.4	130.9	97.5	157.4
wet mass (400 mL) [g]	348.9	276.5	244.1	189.1	286.2
volume absorbed water (water stored in conn. space) [cm³, g]	132.5	130.0	113.2	91.6	128.8
external surface area [cm²]	11168	5157	2848	844	4412
external volume [cm³]	294.0	290.0	295.8	210.2	309.0
vol. interstitial space [cm³]	106.0	110.0	104.2	189.8	91.0
packing fraction	74%	73%	74%	53%	77%
surface area/clast volume ratio	38	17.8	9.6	4.0	14.3
surface area/interstitial volume ratio	105.4	46.9	27.3	4.4	48.5
clast total porosity	79.9%	83.4%	85.9%	86.1%	
clast connected porosity	59.2%	81.0%	83.9%	85.1%	
vol. connected pore space (1 column) [cm³]	174.0	234.9	248.2	178.8	
proportion of conn. space filled with water (accessible)	76%	55%	46%	51%	
proportion of column filled with water during flow (interstitial + conn. pores)	60%	60%	54%	70%	

Our experiments measuring water absorption into 400 mL of dry clasts showed that similar amounts of water are absorbed into the 1-2 mm, 2-4 mm, and mixed sizes of pumice (128.8 g to 132.5 g), with less water absorbed into the 4-8 mm and 8-16 mm (91.6 g to 113.2 g). It is possible that, after saturating the clasts with water during the absorption procedure, interstitial spaces between rocks stored water through capillary forces, particularly in the smaller size ranges with tight packing and small, tortuous interstitial areas; however, we do not believe this interstitial storage exerted a meaningful impact on these absorption results.

With these results, we know how the volume of the column is distributed between solid rock, air, and water (*Figure 29*). Using the packing fraction, we show the proportion of the column that is interstitial space between pumices (light blue) and is occupied by water when the system is flowing. Using the external volume of the pumice clasts, their connected porosity, and the volume of water absorbed during the absorption experiment, we show the volume of water stored within the connected pores of clasts (dark blue), as well as the volume of connected pore space within the clasts that is occupied by air (orange) because the pores were too small and/or too convoluted for water to reach in our experiments.

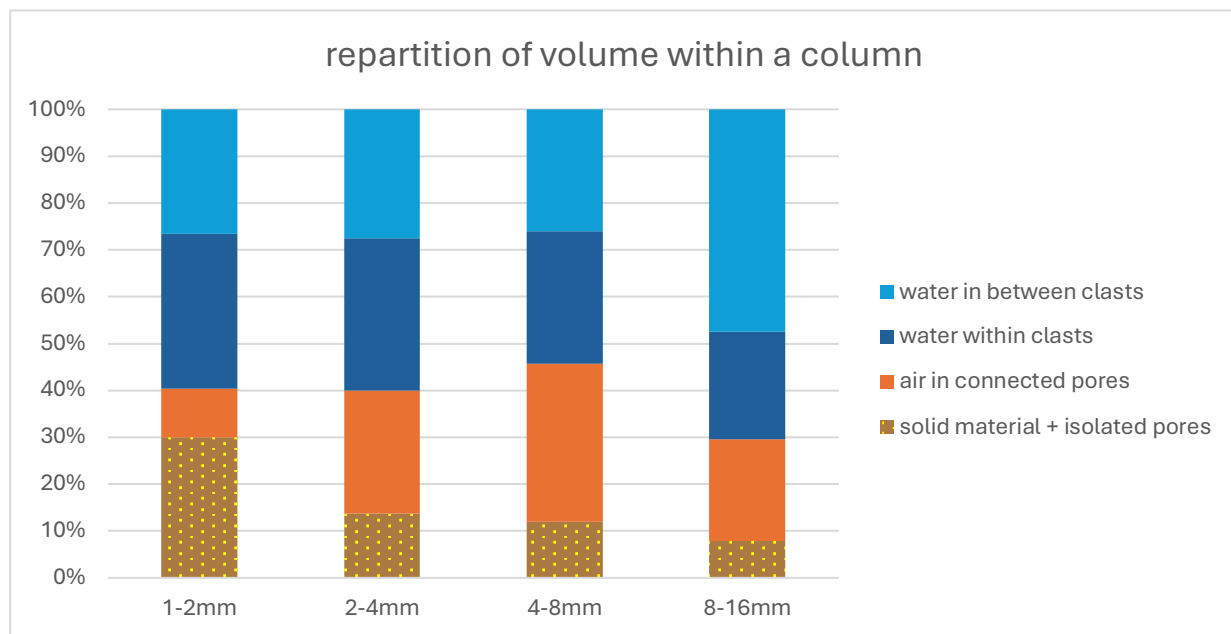


Figure 29: Repartition of volume within a column

Roughly the same amount of water is stored in interstitial space (light blue) and connected pores (dark blue) in columns filled with 1-2 mm, 2-4 mm, and 4-8 mm pumice clasts. More of the total connected pore space as measured using helium (orange and dark blue) within 1-2 mm clasts is filled with water than larger sizes.

Importantly, these analyses demonstrate two main metrics by which 1-2 mm pumice stands apart from the other pumice size fractions:

1. **More surface area:** the 1-2 mm size pumice has more surface area than any other size fraction. The 1-2 mm size fraction also has a ratio of external surface area to interstitial space which is an order of magnitude higher than larger pumice sizes—meaning that water within those interstitial spaces between clasts is much closer to pumice surfaces and makes more frequent contact, resulting in more removal of contaminants.
2. **More absorption into connected pore space:** Comparing data from our absorption and porosity tests (*Table 4*) shows that, of the total connected pore space within pumices that was measured using helium, more of that connected space was reached by water in the 1-2 mm size fraction compared to larger sizes. In *Figure 29*, the total connected pore space is the sum of the dark blue and orange, with orange being the connected pore space which was not filled with water. Our data suggests that 76% of the connected pore space in 1-2 mm pumice is accessible to water, compared to only 46-55% of the connected pore space in the other size fractions (*Table 4*). Exactly what this implies about the distribution of pore space within clasts remains unclear, but we hope that future interpretation of our mercury porosimetry data will illuminate more on the sizes of bubbles in these samples.

4C.ii. Flow Rates

The flow rate of water through the ten columns increases with pumice size, from 9.9 liters per hour (L/hr) in the 1-2 mm size range to 11.0 L/hr in the 8-16 mm (*Figure 30*). This is expected given the higher number of smaller particles, which obstruct flow paths and make it harder for water to flow through the column.

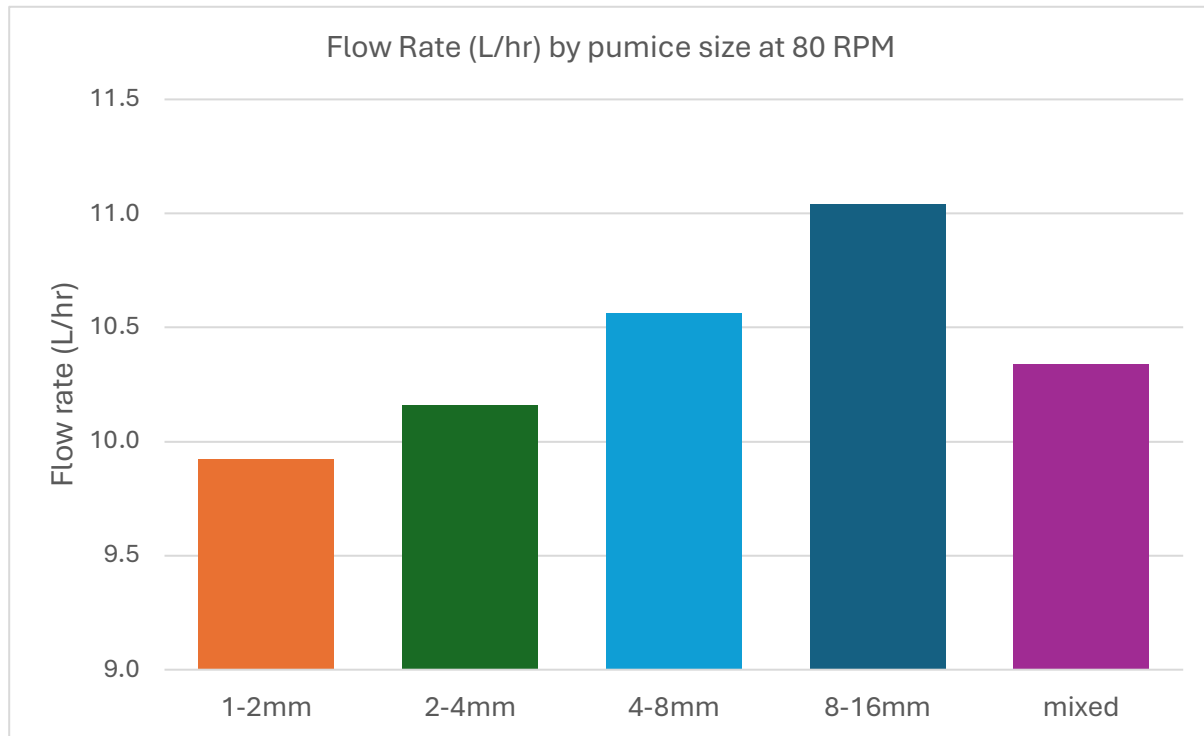


Figure 30: Total flow rate of graywater through 10 columns of pumice, using a peristaltic pump at 80 RPM.

We observed flow rates of graywater between columns holding different sizes of pumice. Despite the peristaltic pump rotating at the same velocity, the graywater flowed fastest in the 8-16 mm size fraction columns and slowest in the 1-2 mm columns. The reported flow rates are averages over several (4-5) time trials in which the system pumped 1 L of deionized (DI) water (Equation 8).

Bubble Size Distribution

We are still in the process of analyzing the data from the mercury porosimetry tests performed on our pumice samples. In the future, we hope to understand from these analyses the sizes of bubbles in the pumices and the tortuosity of the bubble networks— we aim to compare the mercury-derived porosity estimates with those we have measured and calculated using helium pycnometry.

4C.iii. Removal of Contaminants from Graywater Over Time

Turbidity:

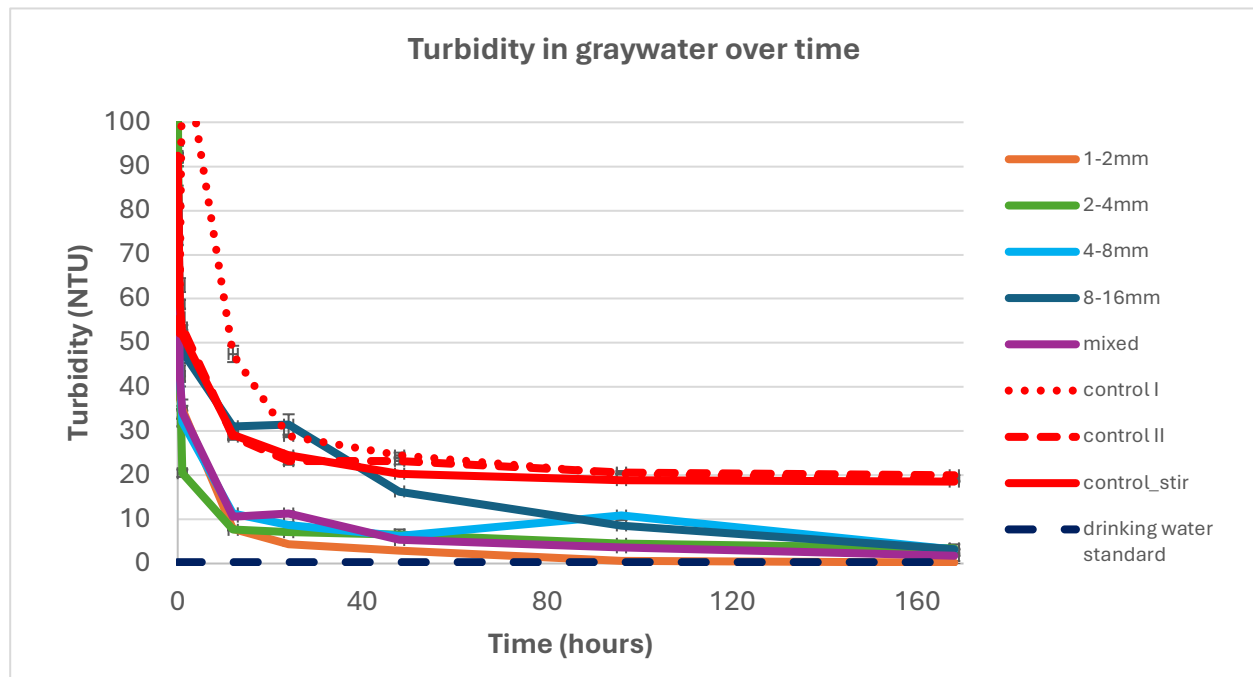


Figure 31: Turbidity in graywater flowing through columns with pumice over seven days, 2024 column flow experiments

The turbidity (nephelometric turbidity units, NTU) of the graywater flowing through all five pumice sizes decreased sharply by between 66% (8-16 mm) and 96% (1-2 mm) in the first 24 hours of the experiment (Figure 31). After the first day, the drop in turbidity reached a plateau, with little change occurring throughout the last six days of the experiment. The 8-16 mm pumice system experienced a slower decrease in turbidity and had higher turbidity levels than the smaller and mixed pumice systems until the fourth day. At the end of the seven-day test, graywater turbidity had been reduced by 96% (4-8 mm and 8-16 mm) to 99% (1-2 mm). The controls we measured experienced a drop of between 79-80%, dropping rapidly within the first 24 hours and hitting a plateau by the 48-hour mark. The drinking water standard (dark blue dashed line) for turbidity is very low (<1 NTU).

Total Nitrogen:

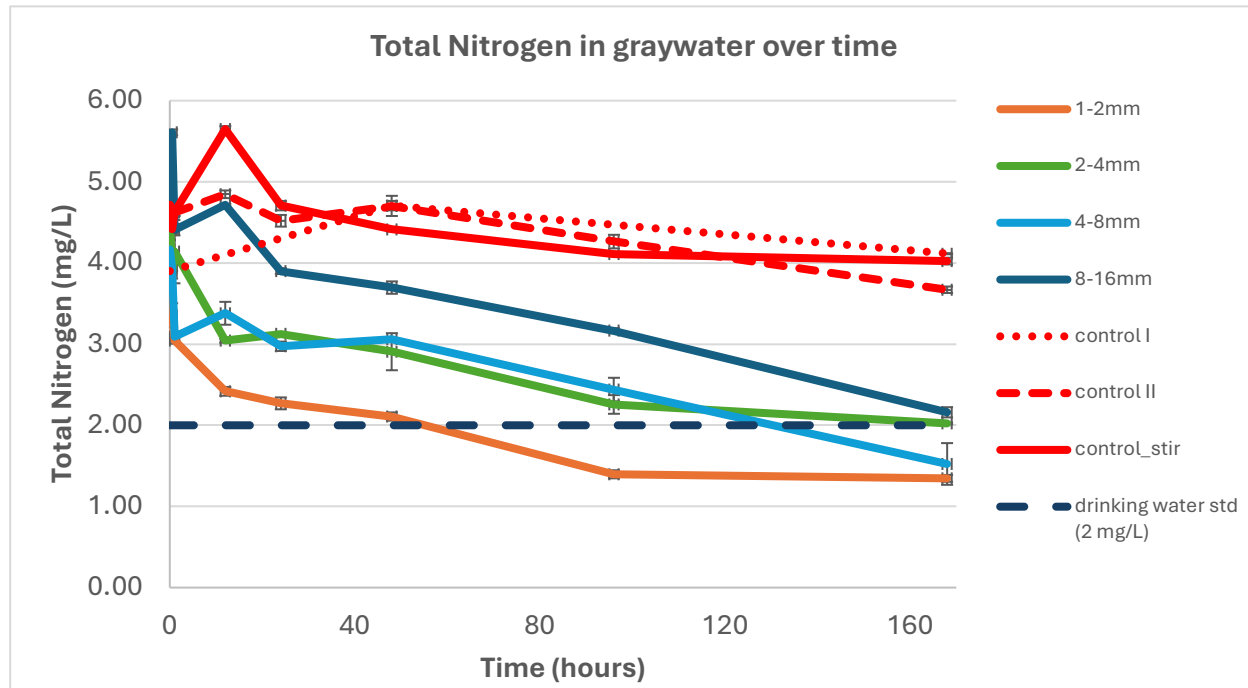


Figure 32: Total nitrogen in graywater flowing through columns with pumice over seven days, 2024 column flow experiments

Total nitrogen (milligrams per liter, mg/L) in graywater flowing through pumice (Figure 32) decreased by between 54% (8-16 mm) and 70% (1-2 mm). In the 2-4 mm, 4-8 mm, and 8-16 mm pumice size fractions, there was an initial steep drop, followed by a gradual decrease; in contrast, total nitrogen in the 1-2 mm size fraction dropped rapidly and then hit a plateau around the four-day mark. Due to a limited supply of test materials, we were unable to test for nitrogen in the mixed size fraction, and our first control test was only sampled (following the measurement of the initial unaltered graywater) after two and seven days. The three control graywater tests (red), stirred and not stirred, experienced between a 22% decrease and 5% increase in total nitrogen over the seven days, with an initial increase during the first 1-2 days, followed by a decrease over the next 5-6 days. The drinking water standard for nitrogen is between 2-6 mg/L (dark blue dashed line).

Phosphate:

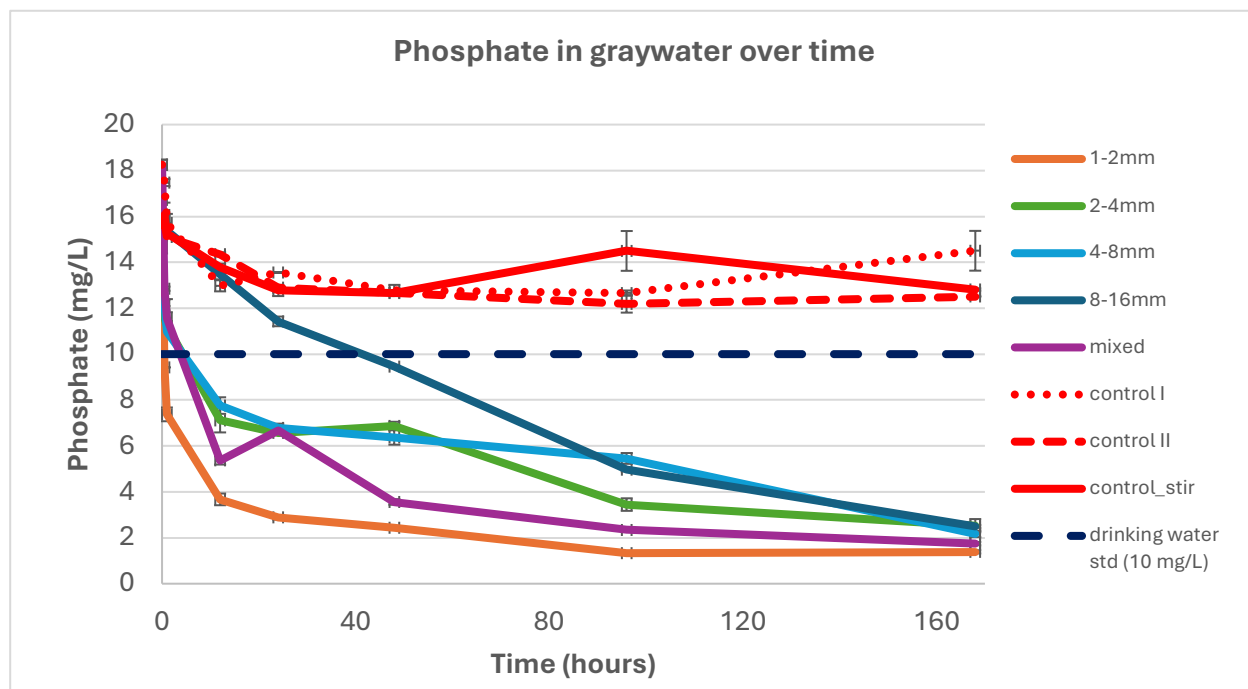


Figure 33: Phosphate in graywater flowing through columns with pumice over seven days, 2024 column flow experiments

Phosphate (milligrams per liter, mg/L) dropped steeply within the first 12 to 24 hours in graywater flowing through pumice, then plateaued by about the 48-hour mark (Figure 33). The rate of phosphate decrease is anticorrelated with pumice size, being highest for graywater flowing through the 1-2 mm and lowest through the 8-16 mm clasts, whereas the total proportion of phosphate removal is high and roughly the same for all sizes, from 83% (2-4 mm) to 92% (1-2 mm). Phosphate in our control graywater, stirred and not stirred, also experienced a rapid drop between 18% to 21% within the first 24 hours of the experiment before plateauing. The drinking water standard for phosphate is around 10 mg/L (dark blue dashed line).

Chemical Oxygen Demand:

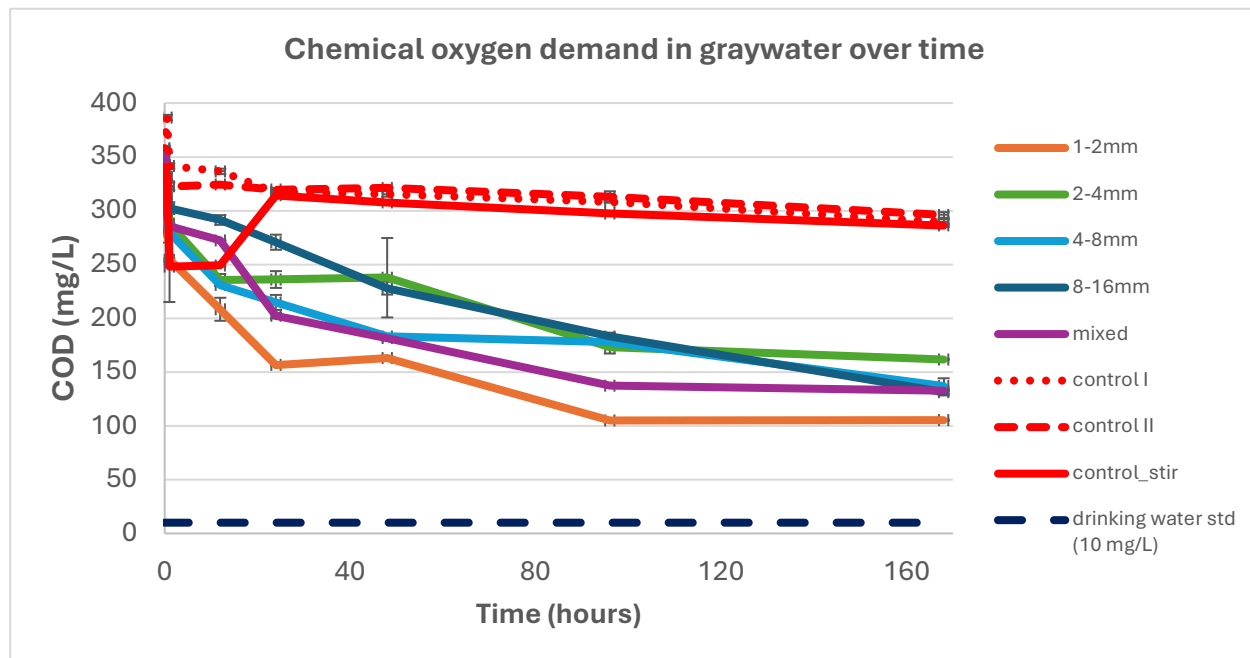


Figure 34: Chemical oxygen demand (COD) in graywater flowing through columns with pumice over seven days, 2024 column flow experiments

Chemical oxygen demand (COD) (milligrams per liter, mg/L) in graywater flowing through pumice (Figure 34) decreased sharply in the first 12 to 24 hours, then gradually fell before plateauing around the fourth day for the mixed size fraction and clasts <4 mm, whereas it still slowly decreased over all seven days in the larger size fraction. Once again, the largest and fastest decrease was observed in graywater flowing through the 1-2 mm pumice clasts. Overall, COD levels dropped by 52% (2-4mm) to 70% (1-2 mm). Control graywater tests showed a smaller (13% - 19%) overall decrease in COD, with the stirred graywater having a rapid drop and subsequent increase of COD within the first 24 hours before behaving similarly to the other two controls for the remainder of the experiment. The drinking water standard for COD is around 10-15 mg/L.

Total Dissolved Solids:

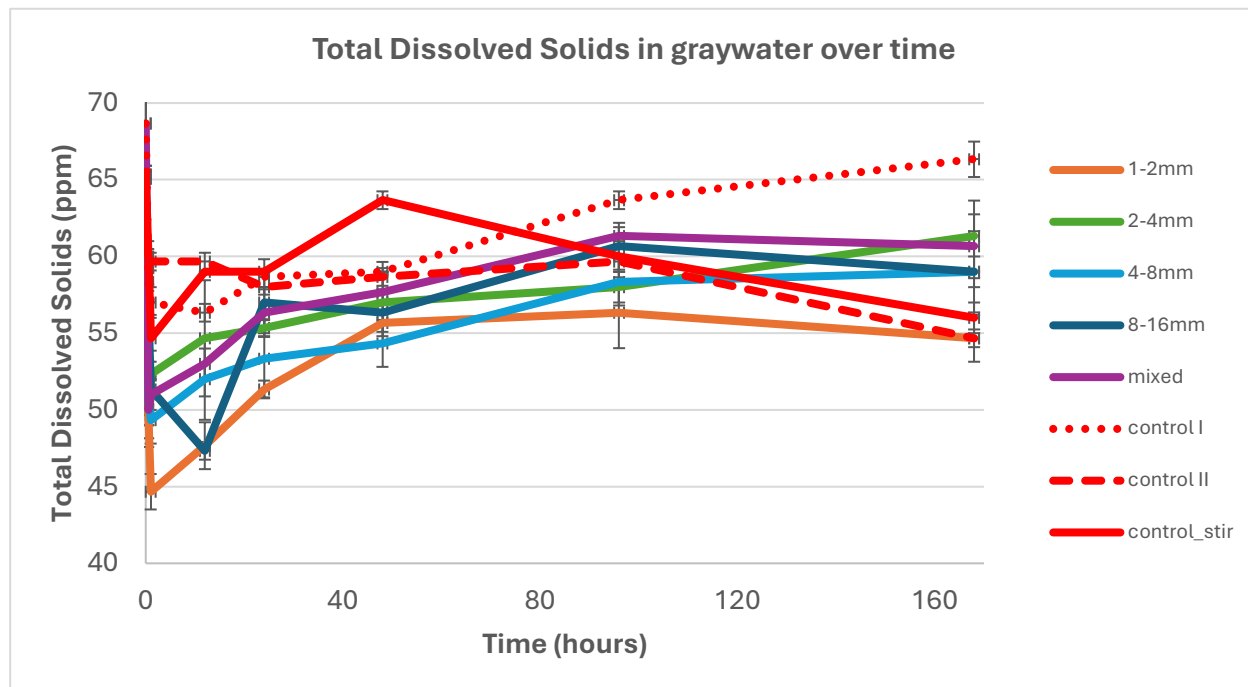


Figure 35: Total dissolved solids in graywater flowing through columns with pumice over seven days, 2024 column flow experiments

Total dissolved solids (TDS) (parts per million, ppm) in graywater flowing through pumice (Figure 35) was variable over the seven days of measurement. TDS in all pumice systems sharply decreased at the 30-minute mark, but increased over the following days, resulting in changes ranging from a 12% decrease (mixed size fraction) to a 13% increase (2-4 mm). Unlike other parameters measured, there was no clear influence of pumice size on the degree of change in TDS. TDS in the control graywater experiments did not trend together and behaved markedly differently than TDS in the pumice system; TDS in the stirred control and Control II graywater fluctuated and eventually decreased 14-16%, whereas Control I graywater TDS dropped rapidly, then gradually increased until the net change was just a 3% decrease from initial graywater TDS. The drinking water standard for TDS varies based on what the dissolved solids in question are, and as such is not shown on this plot.

pH:

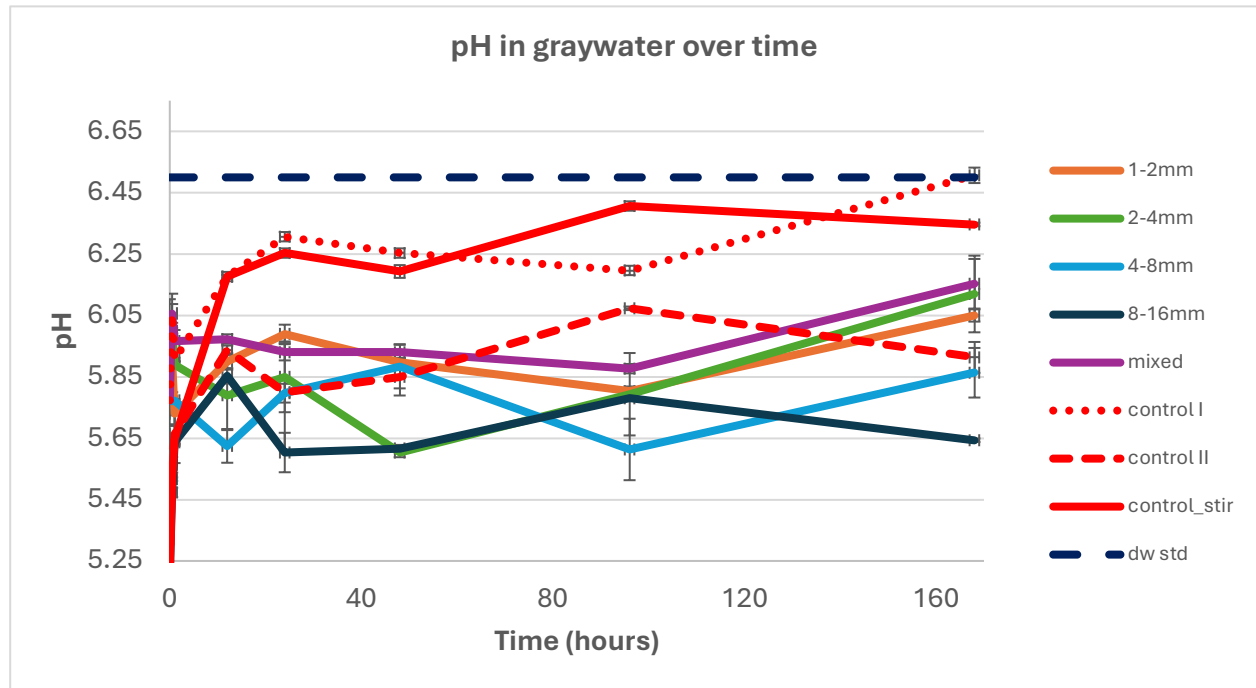


Figure 36: pH in graywater flowing through columns with pumice over seven days, 2024 column flow experiments

Like total dissolved solids, there was not a discernably clear pattern in pH (Figure 36). When in contact with pumice, the pH increased by 0.08 (4-8 mm) to 0.38 (mixed fraction) pH units over seven days with no correlation to pumice size, whereas the control graywater generally experienced an initial increase, then plateaued. Altogether, changes in pH of the graywater were relatively limited in all experiments. “Safe” water should have pH between 6.5–8.

4C.iv. Conservative Bromide Tracer

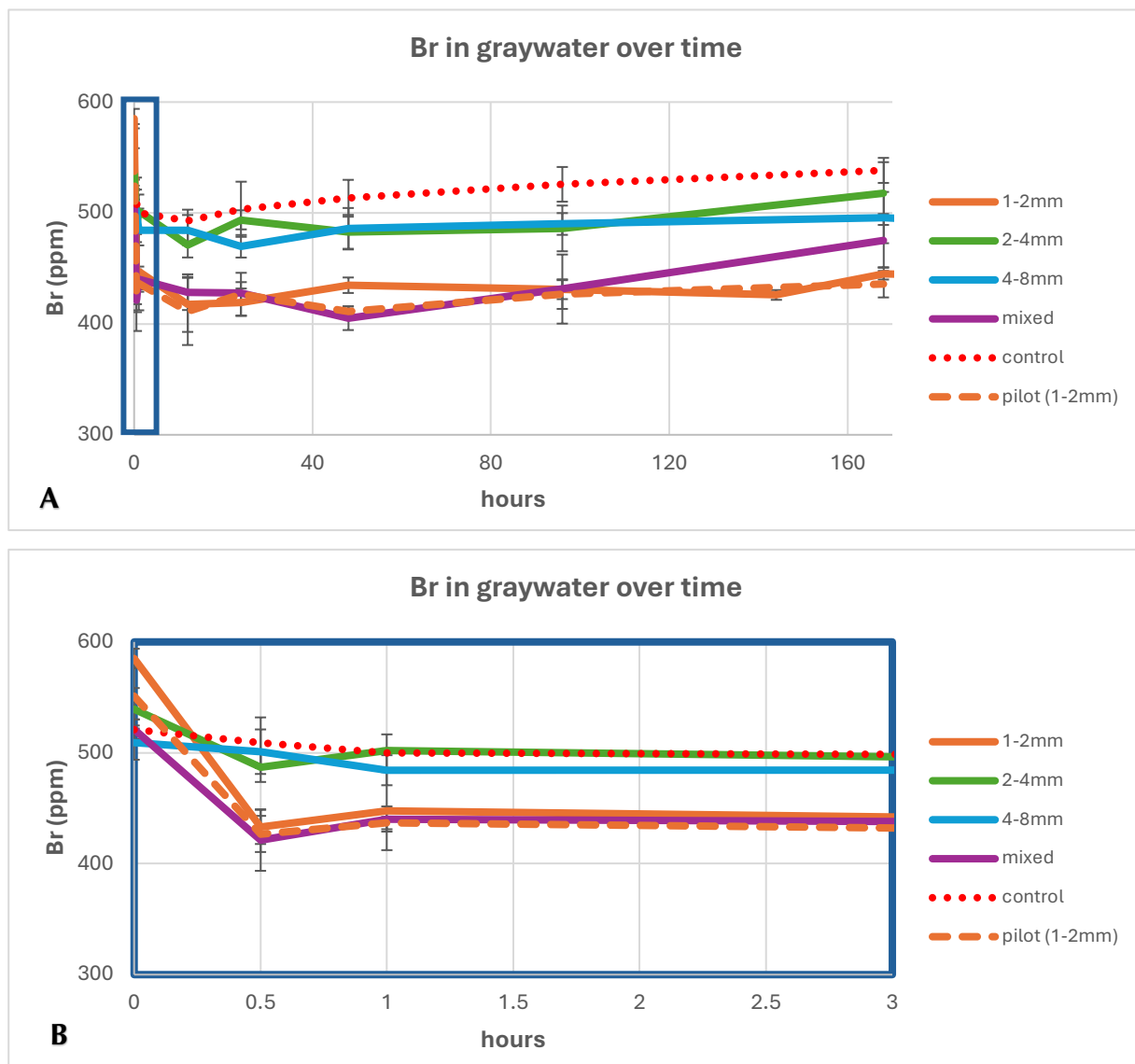


Figure 37: Bromide tracer in graywater flowing through pumice over seven days, 2024 column flow experiments

Bromide (added as KBr to our starting graywater) (parts per million, ppm) decreases initially in graywater flowing through the mixed and 1-2 mm size fractions. Figure 37-A shows bromide over the entire 7-day experiment; Figure 37-B shows bromide levels in just the first three hours (blue box in Figure 37-A). The orange dashed line is our pilot experiment, which tested 1-2 mm pumice. Bromide stays relatively constant in control graywater (red dotted line) and graywater with 2-4 mm, 4-8 mm.

Within the first hour of the experiment, bromide (*Figure 37*) in graywater flowing through the mixed pumice and the 1-2 mm pumice clasts decreased by 16% (mixed) to 24% (1-2 mm), then stabilized. In contrast, there was only a small (4% - 7%) observed decrease in bromide levels in graywater flowing through the 2-4mm and 4-8 mm pumices, as well as in the Control I graywater. ICP-OES analyses were conducted prior to the 8-16 mm, Control II, and stirred control tests, so we do not have bromide data for these experiments.

4D. Interpretation

1. Do the observed interactions between pumice and graywater in still-water conditions occur also in these column filtration systems?

Our graduated cylinder and bottle still-water experiments showed clear increases in total dissolved solids (TDS), dissolved oxygen (DO), and phosphate in graywater sitting in static settings with pumice– however, due to instrument damage, we were unable to collect DO data during our column experiments. Combining data from our still-water and column experiments, we can compare patterns in TDS and phosphate between the two types of tests.

Total Dissolved Solids (TDS):

Our still-water experiments (*Figure 16, Figure 22*) demonstrated consistent increases in graywater TDS over a week. On the contrary, TDS data from our column experiments shows an inconsistent and unclear pattern of TDS change in graywater flowing through pumice (*Figure 35*). We compare these contrasting results in *Figure 38*. TDS in control graywaters behaved similarly to TDS in pumice flow graywater; furthermore, the clear impacts of pumice size (with highest change

occurring in smaller pumice systems) were missing, with no discernable trend in TDS changes resulting from pumice size.

Thus, after flushing the pumice clasts with deionized (DI) water, **flowing graywater through a pumice filter does not increase TDS** over a week, unlike in the static experiments. We hypothesize this could be due to either of the following:

- (1) **Differences between flow and static conditions:** the constant movement of water in the column systems did not allow the interactions at the pumice-graywater interface which resulted in the TDS increase observed in the static experiments.
- (2) **Changes in rock sample preparation methods:** the column experiments included a flushing step which gently washed ambient fine ash particles off the pumice surfaces prior to interaction with graywater. Pre-experiment flushing of fines was not a component of the still-water experiments. The observed increase in graywater TDS with time in the static experiments could be thus partly related to interactions between the graywater and the ash which did not occur in the flow experiments.

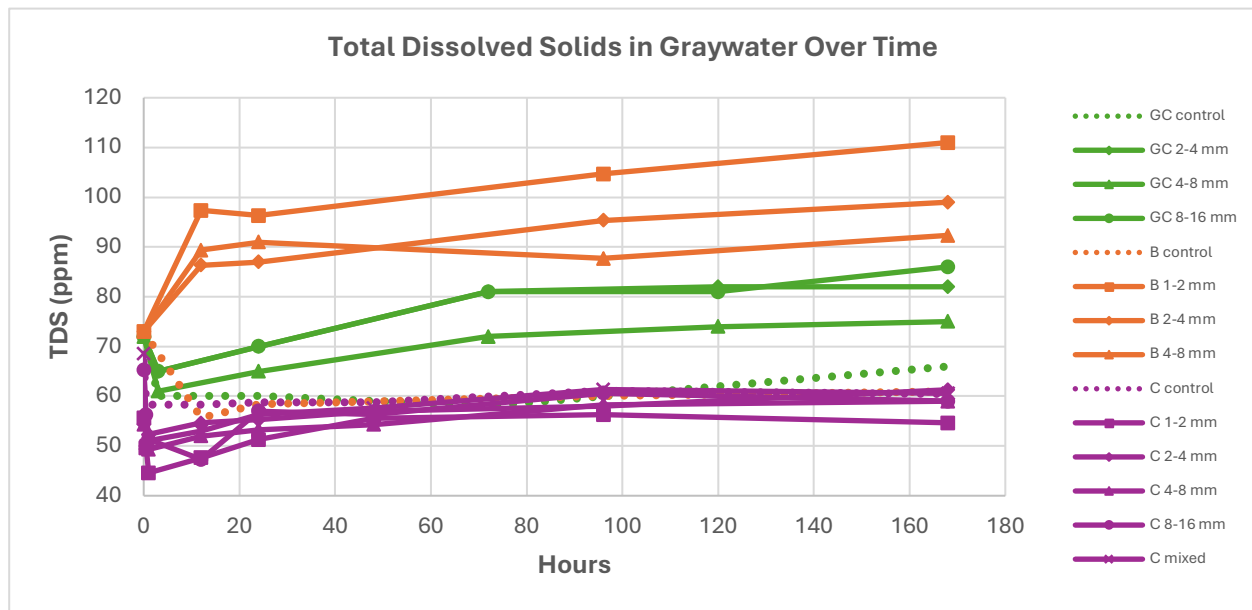


Figure 38: Comparing TDS levels in graywater between experiments

Total dissolved solids (TDS) in graywater over seven days in our graduated cylinder still-water (GC, green), bottle still-water (B, orange), and column flow (C, purple) experiments. Dotted lines represent the control graywaters (without pumice) in each set of tests. We suspect the high increase in TDS in our bottle experiments is a result of chemical interactions between the graywater and abundant ash particles from pumice clast abrasion within the bottle (ash particles which were not present in the graduated cylinder or

column experiments because we washed ash off the clasts as part of our experimental procedure. Controls from all three experiments behave similarly.

Phosphate:

In our still-water bottle experiments, graywater phosphate levels increased over time (*Figure 23*), whereas our column experiments show a clear decrease in graywater phosphate levels (*Figure 33*). We compare these results in *Figure 39*. This decrease indicates that **graywater materials containing phosphate are being efficiently removed from the water by the pumice** filtration columns. Exactly why phosphate levels increased in our still-water experiments is unclear, but it is possible, similarly to TDS, that there were impacts to the graywater from the abundant fine ash particles which were not removed from the pumice prior to performing the bottle experiments. Those fine ash particles potentially provided surface area for interactions with the graywater that dissolved phosphate from the fine ash into the graywater. More work needs to be done here to understand the potential for dissolution of phosphate into the graywater– in 2023 we sent some of our pumice samples for XRF (X-ray fluorescence) analysis (**Appendix V**) and, although we received data back, we have not interpreted the samples' resulting chemical compositions in light of our phosphate data.

Regardless of the causes for the phosphate increase in the still-water experiments, it remains clear that graywater phosphate levels in our pumice column filtration experiments decrease and thus that, once cleaned of fine ash, **pumice clasts are efficient at removing phosphate from graywater.**

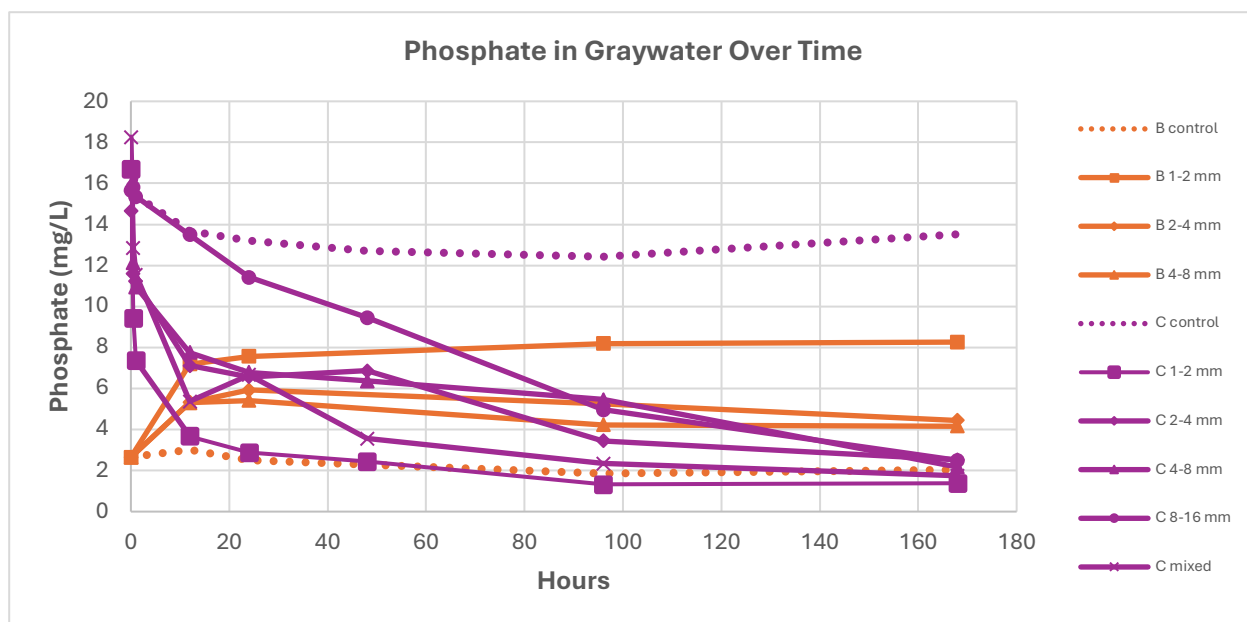


Figure 39: Comparing phosphate levels in graywater between experiments

Phosphate in graywater over seven days in our bottle still-water (B, orange) and column flow (C, purple) experiments. Dotted lines represent control graywaters (without pumice). In the bottle experiments, graywater in contact with pumice shows increases in phosphate, while control graywater phosphate remains constant; In the column experiments, phosphate in graywater with pumice decreases while control graywater phosphate remains constant.

2. Does our pumice column filtration system effectively clean graywater?

Our pumice column filtration system **effectively removed contaminants** from graywater: turbidity, total nitrogen, phosphate, and chemical oxygen demand were significantly removed from the graywater in all pumice trials (**Section 4C.iii**). These decreases far exceed those observed in the control graywater experiments.

Although our column filtration system did not always reduce contaminants to within drinking water standards (**Section 4C.iii**), it is worth noting that graywater reuse systems inherently are designed for graywater to be cleaned and used for water needs not requiring potable water, such as agricultural irrigation and toilet flushing (**Section 1A.ii**).

While drinking water standard are accessible and helpful metrics to contextualize our results in light of other water quality measures, they do not provide a full picture of the potential applications of this project to real-world wastewater recycling.

We flushed the pumice columns with deionized (DI) water prior to graywater filtration, then let the columns drip dry overnight, but some DI water remained trapped within in the clasts when we started the graywater filtration the next day. In samples of graywater flowing through 1-2 mm pumice, mixed size pumice, and a control test we did with 1-2 mm pumice, there was a rapid initial drop in levels of the bromide tracer measured at the 30-minute sampling interval (*Figure 37*). We believe **this bromide decrease reflects the flushing of absorbed DI water from the clasts** into the graywater, adding new “clean” water to the system and thus diluting the overall bromide concentration. This flush did not occur in graywater flowing through larger pumices (2-4mm and 4-8 mm) because those pumice columns, having larger clasts (and resulting larger interstitial spaces between clasts which facilitate easier gravitational loss of water), lost more of the DI water which had been absorbed into clast structures over the night before filtration as they were drip drying. Decreases in bromide levels in the graywater at the beginning of each experiment thus demonstrate that the DI water within the clasts was displaced by the graywater, confirming that **water quickly flows *through* pumice clasts** in the filtration columns, **in addition to *around* them**, and thus can encounter bubble walls in pores on the interior of the pumice clasts– interfaces where filtration (the trapping of contaminants on surfaces) can take place.

For the most part, **effective removal of graywater contaminants occurs within the first two days** (48 hours) of the experiment, with most contaminant measures plateauing around or before that sampling interval. Some, like turbidity and chemical oxygen demand, reach plateaus as early as the 24-hour mark. This rapid removal of contaminants suggests that **real-world water treatment systems using pumice clasts could run for just a few days** and still achieve meaningfully clean graywater that could then be reused or released into ecosystems.

3. How is filtration efficacy influenced by pumice size and why?

The degree to which contaminants are removed is controlled by the size of pumice in the filtration columns. Our **smallest (1-2 mm) pumices remove more contaminants and faster** than larger size fractions. Furthermore, the data from our mixed size pumice test show that the 1-2 mm portion of the mix (1/4 of the sample by volume) is contributing to more efficient filtration than columns filled with just larger pumices. We believe this higher efficiency is due to the **increased amount of total surface area of rock in contact with water** in the 1-2 mm size fraction compared to larger clast sizes. Each column of 1-2 mm pumice has both more internal surfaces (due to a greater amount of connected pore space within clasts) *and* more external surfaces (due to a tight packing fraction and large number of small clasts, each of which increase the amount of surface on the outside of clasts within the column). The observed ratio of external surface area to interstitial space (*Table 4*), which is an order of magnitude higher for 1-2 mm than other pumice sizes, suggests

that **water in interstitial spaces between 1-2 mm clasts** is in closer proximity with, and thus makes more contact with, external pumice surfaces.

Graywater flowing through columns filled with 1-2 mm pumice flows the slowest out of all the pumice sizes (*Figure 30*). Because the peristaltic pump was rotating at the same speed for all the experiments, the observed difference in flow rates results from more convoluted flow paths for graywater in the smaller pumice sizes. This result seems intuitive: tight packing of many small clasts means that, for water to make its way through the column, it must take windier, more twisting flow paths, which take more time to traverse. Thus, **graywater is also spending more time in contact with the surface of the pumice** (whether on the inside or the outside of the clasts) when in a column filled with 1-2 mm rocks than in columns filled with larger rocks.

4. How does pumice compare to other natural graywater filters?

Pumice has rarely been applied in the literature as a granular filtration material for graywater. However, the observed efficacy of our pumice system can be compared to published trials which use other natural materials in a granular graywater filtration system (*Figure 40*).

Our system removes a large amount of turbidity and chemical oxygen demand (COD) within the first 48 hours of flow. **Similar results have been found in two other published studies** that performed granular graywater filtration trials over comparable time scales using sand and gravel (Tusiime et al., 2022) and mixed materials including clamshells,

steel slag, limestone, and sand (Mohamed et al., 2016). In both cases, these filters reduced turbidity and COD similarly to our pumice column system (*Figure 40*).

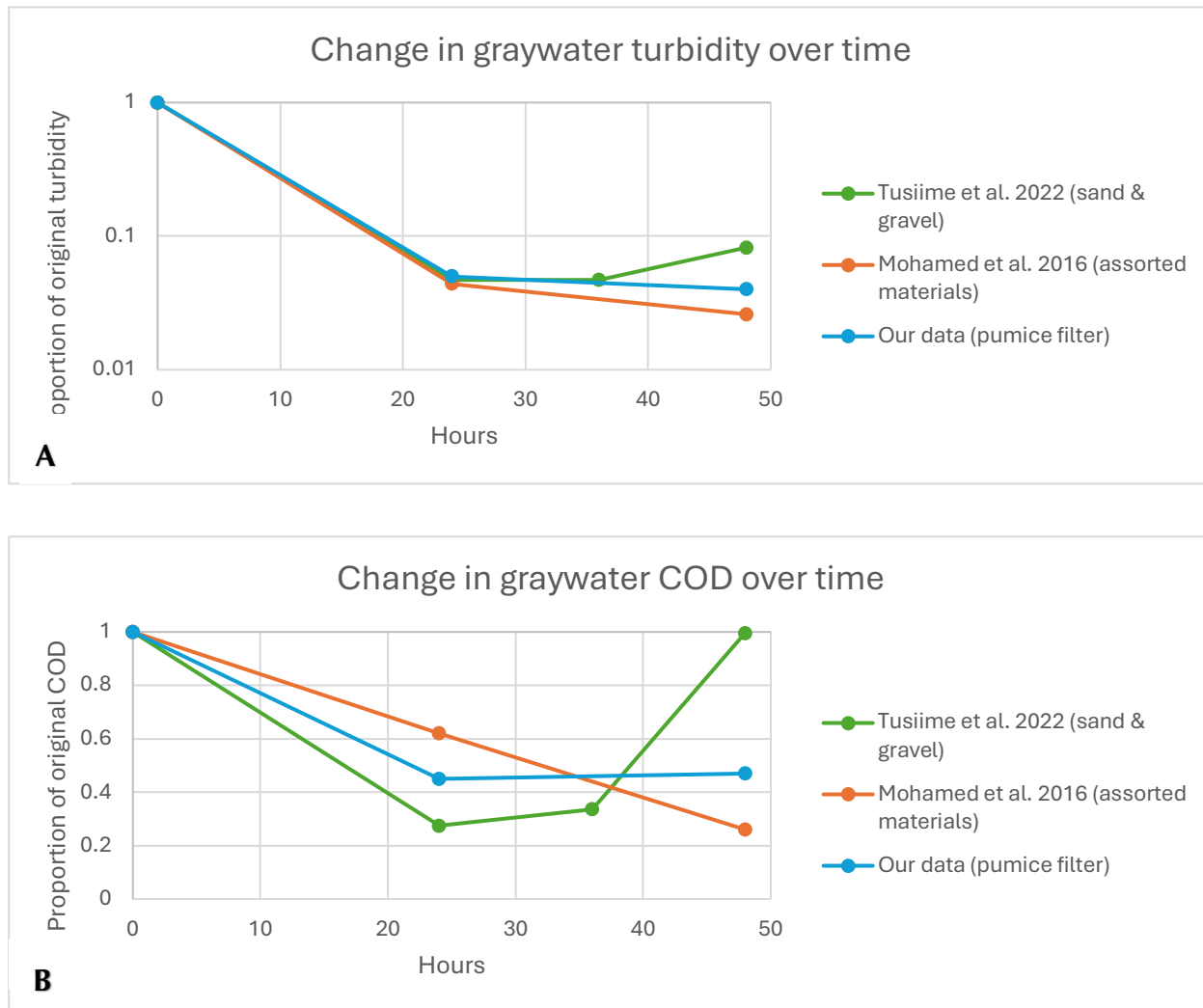


Figure 40: Comparing changes in graywater turbidity and COD between other publications

Our pumice column experiments (blue) performed similarly to other published natural material granular filter systems in removal of turbidity and chemical oxygen demand (COD) (Tusiime et al., 2022, green; Mohamed et al., 2016, orange). This suggests that pumice is as effective at filtering graywater as other granular natural materials and can be considered a candidate medium for creating new filtration systems.

Further review should be done to better contextualize our results in the broader graywater filtration literature. The graywater recipe or source, size of grains used, volume of filtration

system, flow rate, and other experimental details should be more closely compared.

Regardless, it is clear that **pumice is one of many low-cost natural materials that can effectively clean graywater**. This is crucial when considering the potential applications of this research to real-world graywater systems: communities with straightforward access to pumice (for example, those in remote volcanic areas with abundant pumice deposits) would be able to use that resource to create wastewater treatment systems to reduce both potable water consumption and the environmental impact of releasing wastewater effluent. Pumice's porosity and granular nature make it easier to transport than heavier materials like sand or dense rock gravel, further heightening its accessibility as a filter media.

5. CONCLUSIONS

Treating graywater for reuse is environmentally and societally beneficial, reducing potable water consumption and effluent pollution. Our column filtration system using Mazama Climactic pumice efficiently removed turbidity, total nitrogen, phosphate, and chemical oxygen demand from synthetic graywater flowing around 10 liters per hour over seven days. Of the five sizes of pumice we tested, 1-2 mm pumice was the most effective, removing more contaminants faster than larger or mixed size fractions. Physical analyses of the pumice samples suggest this advantage is a result of increased surface area on the smaller clasts, providing more pumice-graywater interface where contaminants can be trapped. Tight packing of the 1-2 mm size fraction also results in small and convoluted interstitial spaces, meaning that water flowing between clasts makes more contact with rock than with larger pumice sizes.

In our system, most contaminant removal occurred in the first 48 hours of column flow (at ~10 L/hr), suggesting that real-world graywater treatment systems using pumice could operate for just a few days and still achieve effective filtration. These results are comparable to other published granular graywater filtration systems using natural materials; pumice seems to be as effective at removing graywater contaminants as sand, gravel, and other mixed material filters, many of which are more difficult to transport.

Although more work remains to be done investigating the lifespan and practical implementation of these systems, our experiments suggest pumice is an effective and accessible filter material which should be considered in designing future graywater treatment systems.

6. FUTURE WORK

Although our results offer considerable insight into the experimental use of pumice as a graywater filter, much work has yet to be done surrounding the practical implementation of a real-world water treatment system.

What controls plateaus in contaminant levels?

Further column flow filtration experiments can be conducted to better understand the plateaus in contaminant levels reached during the first few days of our tests. Our results do not make clear whether contaminant levels flatten out because of some attained limit within the *pumice* (e.g. the pumice is “full” and cannot store any more contaminants) or within the *graywater itself* (if all the contaminant in question that *could be* removed has been removed). This could be tested by flowing graywater through pumice columns and testing contaminant levels until they reach the observed plateau, then switching the same graywater tubing to flow through new, unused pumice and observe whether contaminant concentrations stay stable (supporting a limit within the graywater) or drop further (supporting a limit within the pumice).

Would crushed large pumice perform differently?

Our results highlight both characteristic differences in porosity and varying capacities for contaminant removal between size ranges of pumice. Many papers in the literature, when utilizing pumice, crush large pumice into smaller size fractions. Doing so could, in theory, provide the high external surface area of small clasts while also preserving higher connected porosity of larger clasts; this combination could potentially maximize the amount of total (internal and external) surface area

and, as a result, increase filtration efficacy. However, our data also demonstrate differences in accessible porosity (the amount of a clast's connected pore space which water can actually reach), so it remains to be seen how the crushing of larger pumices would affect the proportion of connected porosity that is accessible to water and the resulting impact on filtration efficacy.

Does scoria perform similarly to pumice?

In my undergraduate thesis research on this topic, we also studied chemical interactions between scoria and graywater. Although we conducted one preliminary test of graywater filtration through columns of 8-16 mm scoria during my master's experiments, those data are not included in this thesis. Scoria, which have larger pores but overall lower porosity than pumice, have comparable exterior surface area and are also produced at a wide range of volcanoes in countless locations around the world. Testing scoria filtration systems could offer more options for real-world implementation of graywater treatment systems in communities with different types of available natural materials.

What is the distribution of bubble sizes in our samples?

Finally, as previously mentioned, more work remains to analyze the mercury porosimetry data collected on our pumice samples. We hope to soon spend more time working through this data to better understand the size, tortuosity, and distribution of connected pore spaces throughout the rocks, and to connect this information with our findings on graywater filtration efficacy across different pumice size fractions. The same is true for our XRF data, particularly considering the phosphate increase observed in our still-water bottle experiments— further analysis of our samples' chemistry may illuminate more about the source of the phosphate that is entering the graywater.

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8. APPENDICES

Appendix I. Conventional Wastewater Treatment Methods

Conventional wastewater treatment systems typically involve several steps (*Figure A-1*).

First, in a series of steps called “primary” treatment, sewage water flows through a screen which removes floating objects like sticks, then to a grit chamber where heavier materials like sand and rocks settle out, and then to a sedimentation tank where raw primary biosolids are removed (EPA, 1998). The next step, known as “secondary” treatment, can vary based on the system, but generally involves biological purification of the effluent from primary treatment. Secondary treatment typically is done through either a trickling filter system (where sewage flows downward through a filter of small pieces like stones or plastic, where bacteria living on the material surface clean the water) or an activated sludge process (where sewage flows through an aeration tank, where it mixes with air and bacteria-laden sludge and is cleaned by the bacteria) (EPA, 2004). After primary and secondary treatment, the effluent is typically sanitized using chlorine, ozone, or UV light.

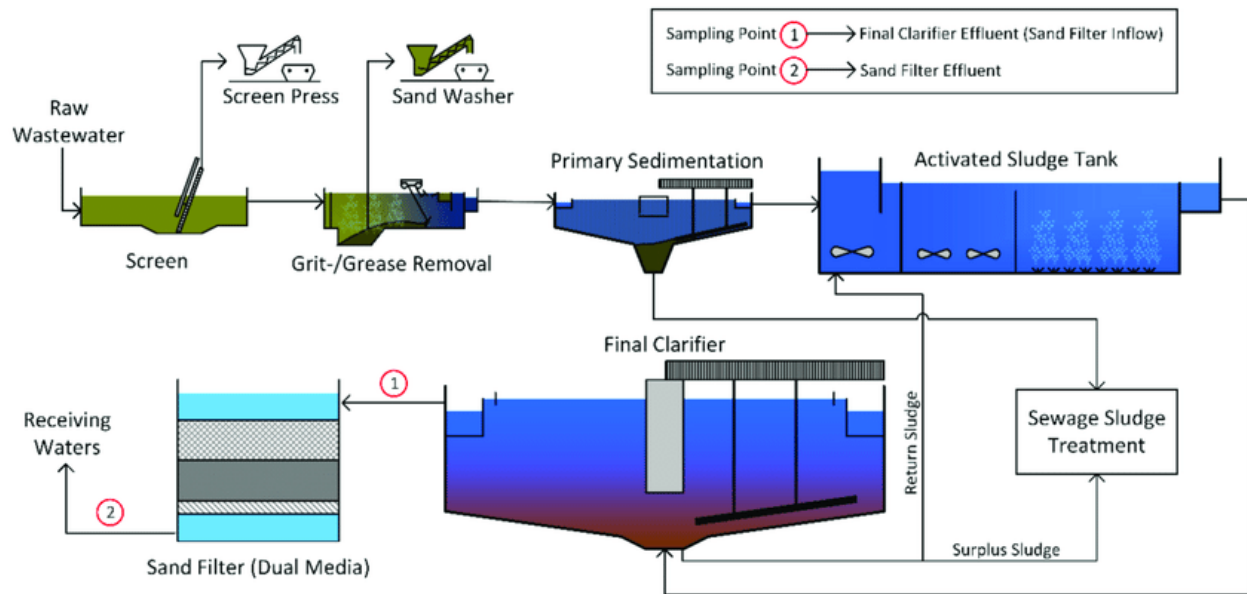


Figure A-1: Diagram of conventional wastewater treatment system from Wolff et al., 2020

Conventional wastewater treatment systems include screening of large solids and greases, primary and secondary sedimentation and clarifying processes, and final removal of contaminants using filtration and/or disinfection before releasing effluent.

Some wastewater treatment systems use alternative processes in addition to primary and secondary treatment: these alternates include lagoons (outdoor water storage tanks which utilize natural biologic decomposition processes), land treatment (where effluent is applied to landscapes and naturally filtered as it percolates down and re-enters the water table), and constructed wetlands (*Figure 5: Examples of constructed wetlands systems*, systems in which plants are grown in a sediment and wastewater flows through the sediment, being treated by both the plants and the sediment) (EPA, 2004). In the case of extremely hazardous or polluted wastewater, particularly from industrial sources, it is common to apply further, more advanced treatment, including processes like adsorption, coagulation and flocculation, use of special membranes, ion exchange, reverse osmosis, sequencing batch reactors, and up-flow anaerobic sludge blanket reactors (EPA, 2004; Ghaitidak &

Yadav, 2012). Once treatment is complete, the effluent is pumped back into ecosystems—most commonly into local watersheds.

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Appendix II. References for Figure 3: Map of Graywater Recycling Laws in U.S.

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Appendix III. Source Information for Pumice Samples

The pumice samples used throughout this project were collected at a range of different locations around the central Oregon Cascades.

Graduated Cylinder Still-Water Experiments

The experiments in my undergraduate thesis work (2021-2022) used two sample sets of pumice from Mount Mazama and one sample set of scoria. Pumice samples from the Climactic Mazama deposit (~7.7 ka; samples referred to in that work as *PumA*) were collected from the South Chemult Pumice quarry, near Chemult, Oregon, in 2021 by my advisor, Dr. Thomas Giachetti, and his then-graduate student Josh Wiejaczka. Samples of the Cleetwood deposit (eruption preceding the Climactic eruption; samples referred to as *PumB*) were collected from a tephra pit dug by Thomas and Josh about 45km southeast of the vent which is thought to have been the source for the Cleetwood eruption.

The scoria were collected by Josh and my advisor from a cinder cone about 3km south of the South Chemult Quarry. Less is known about their age or origin because cinder cones are much smaller and more common in this region of the Oregon Cascades.

Bottle Still-Water Experiments

All the pumice used in the 2023 bottle experiments was from the Climactic Mazama eruption. The samples used for pilot and preliminary experiments were collected directly

from a tephra pit in the Climactic deposit near Chemult, Oregon during the UO Earth Sciences undergraduate field camp in summer 2022.

The samples used for the main bottle experiments were purchased from Lane Forest Products (LFP), a home and garden supply company in Junction City, Oregon in January 2023. LFP sells a pre-sieved (roughly 2-8mm) size fraction of the Climactic Mazama deposit which is distributed by the South Chemult Pumice quarry. Before purchasing, we were unaware of the size range and encountered issues in not having enough of the 1-2 mm sample size (as very little of that size range was present in the sample we purchased). As a result, we adjusted the experimental bottle procedures to accommodate the amount of sample in our possession.

Column Experiments

Some of the pumice used in our column experiments was Climactic Mazama pumice purchased from Lane Forest Products in January 2023. The remainder was donated by South Chemult Pumice Quarry and collected in January 2024 from the quarry site near Chemult, Oregon, along with samples of scoria for use in other laboratory research projects.

Appendix IV. Further Bottle Still-Water Time Series

Plots depicting pH, total nitrogen, and chemical oxygen demand in our 2023 bottle still-water experiments. Turbidity data are not included because the ash present on the surfaces of the pumice generated turbidity in the graywater beyond the limits of our instrument.

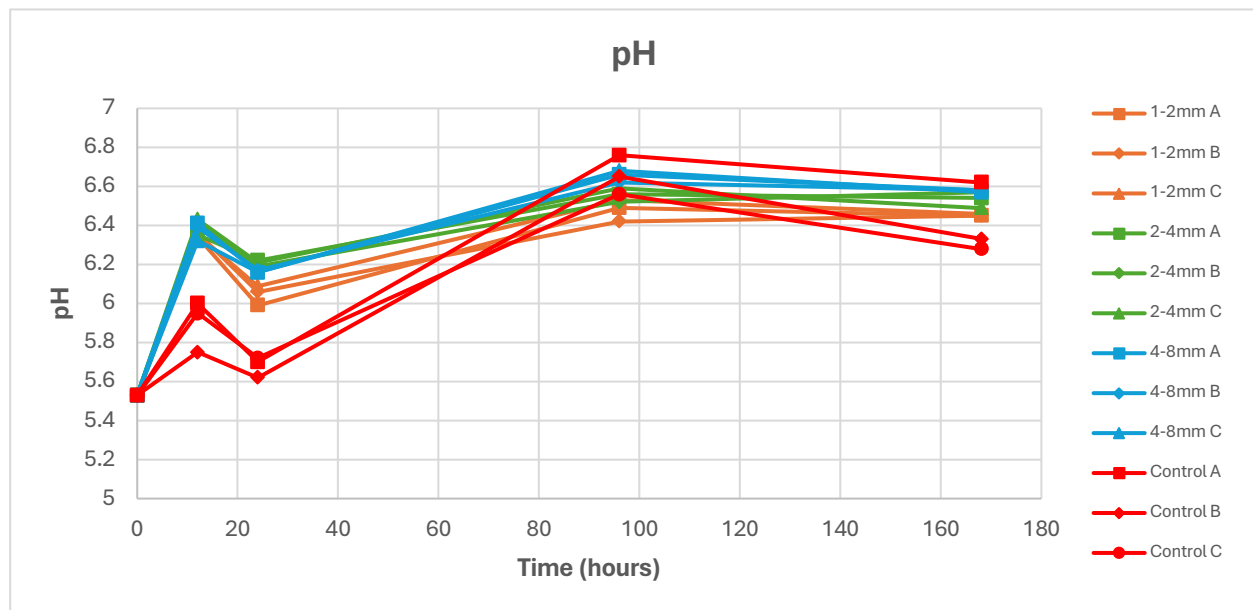


Figure A-2: pH in graywater, 2023 bottle still-water experiments

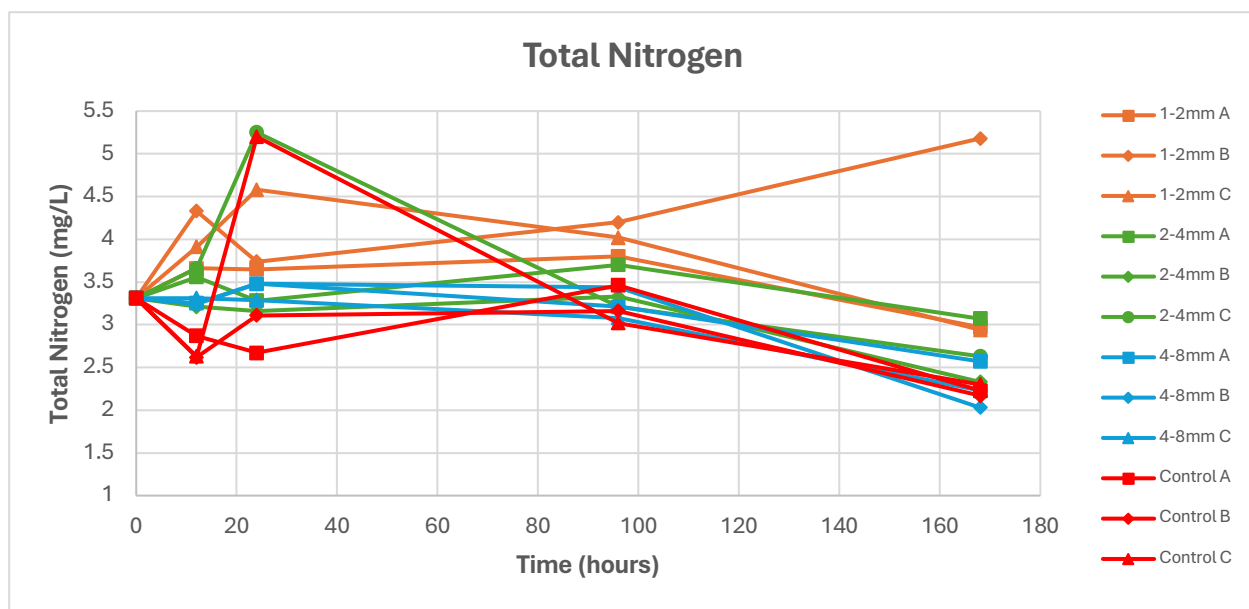


Figure A-3: Total Nitrogen in graywater over time, 2023 bottle still-water experiments

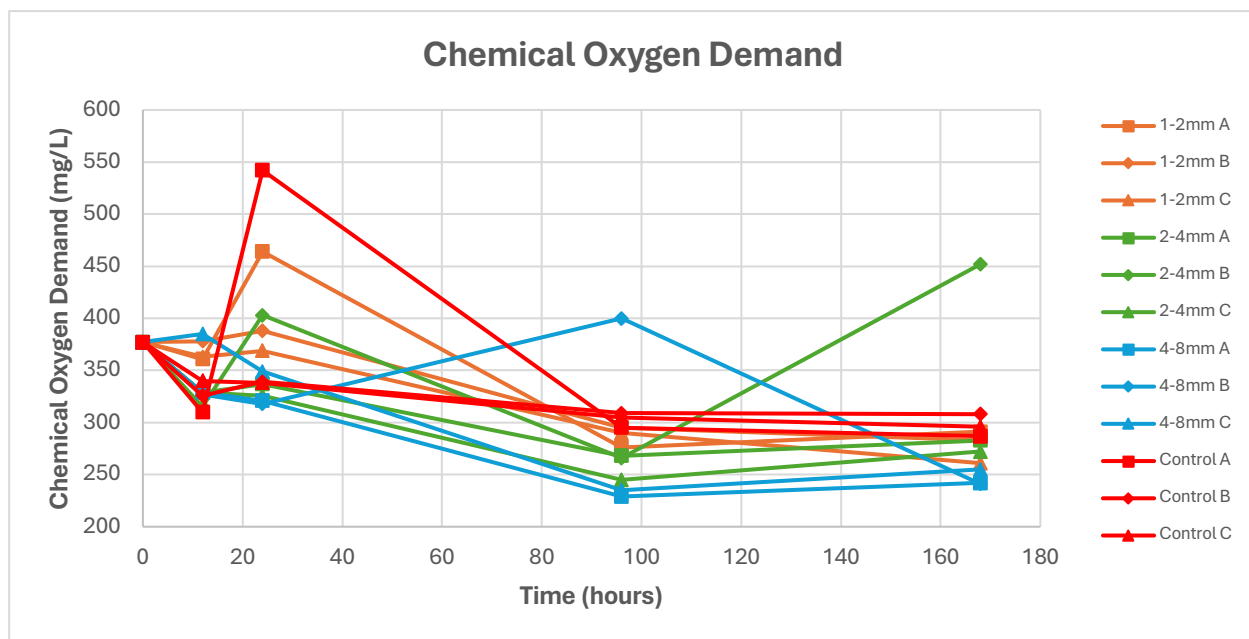


Figure A-4: Chemical Oxygen Demand in graywater over time, 2023 bottle still-water experiments

Appendix V. XRF Data

Data from x-ray fluorescence (XRF) analyses of our 1-2 mm, 2-4 mm, and 4-8 mm Mazama Climactic pumice samples, conducted 2023.

Table A1: XRF major elements in Mazama Climactic pumice

NORMALIZED MAJOR ELEMENTS (WT %)			
	1-2 mm	2-4 mm	4-8 mm
SiO ₂	69.15	70.58	70.68
TiO ₂	0.49	0.51	0.50
Al ₂ O ₃	16.30	15.29	15.36
FeO*	2.66	2.80	2.68
MnO	0.06	0.06	0.06
MgO	0.87	0.84	0.76
CaO	2.96	2.33	2.29
Na ₂ O	5.07	4.91	5.00
K ₂ O	2.34	2.56	2.57
P ₂ O ₅	0.11	0.11	0.11
TOTAL	100.00	100.00	100.00