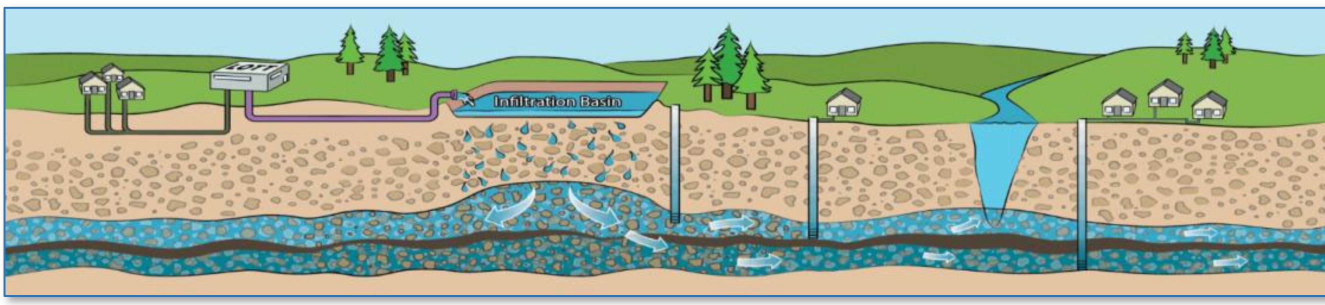
LOTT Clean Water Alliance
Reclaimed Water Infiltration Study

Project Summary

AUGUST 23, 2022



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Key Acronyms and Abbreviations

ADD	average daily dose
AOP	advanced oxidation process
AWQC	ambient water quality criteria
BAC	biologically activated carbon
BAF	bioaccumulation factor
BIRWP	Budd Inlet Reclaimed Water Plant
BITP	Budd Inlet Treatment Plant
CAG	Community Advisory Group
COI	chemical of interest
COPEC	chemical of potential ecological concern
CSM	conceptual site model
DWEL	Drinking Water Equivalent Level
EAE	ecological assessment endpoint
EPC	Exposure Point Concentration
ERA	Ecological Risk Assessment
g/d	grams per day
GAC	granular activated carbon
H_2O_2	hydrogen peroxide
HHRA	Human Health Risk Assessment
HI	hazard index
HQ	hazard quotient
LADD	lifetime average daily dose
LECR	lifetime excess cancer risk
LOAEL	lowest-observed-adverse-effect level
LOTT	LOTT Clean Water Alliance
mg/kg-d	milligrams per kilogram body weight per day
mg/L	milligrams per liter
mgd	million gallons per day
MCL	maximum contaminant level
MLE	more likely exposure
MRL	minimum reporting limit
MWRWP	Martin Way Reclaimed Water Plant
NDMA	N-Nitroso dimethylamine
NOEC	no-observed-effect concentration
O&M	operations and maintenance
O_3	ozone
PFAS	per- and polyfluoroalkyl substances
PFBS	perfluoro-1-butanesulfonic acid
PFHxA	perfluoro-n-hexanoic acid

PFOA	perfluoro octanoic acid
PFPeA	perfluoropentanoic acid
PRA	probabilistic risk assessment
PV	present value
Q_c	Sea Level (or “Deep”) Aquifer
Q_{va}	Vashon Advance (or “Shallow”) Aquifer
RME	reasonable maximum exposure
RO	reverse osmosis
ROC	receptor of concern
RWIS	Reclaimed Water Infiltration Study (or Study)
STF	Science Task Force
TRV	toxicity reference value
TSC	Technical Sub-Committee
UCL	upper confidence limit
U.S. EPA	United States Environmental Protection Agency
UV	ultraviolet light

1.0 Introduction

The LOTT Clean Water Alliance (LOTT) conducted a study to answer community questions and concerns about residual chemicals that may remain in reclaimed water after treatment, and what happens to them when reclaimed water is infiltrated into the ground. Residual chemicals is the term used to refer to chemicals that come from pharmaceuticals, personal care products, household products, and commercial/industrial uses. This extensive scientific effort, referred to as the Reclaimed Water Infiltration Study (RWIS, or Study), took place over a 10-year period, with initial scoping in 2013, and concluding with final technical reporting and community outreach efforts in 2022. This Project Summary provides an overview of Study activities, highlights key findings, and identifies how the Study results are informing next steps and actions LOTT is considering regarding long-term management of wastewater resources.

1.1 Background

LOTT provides services to treat and manage wastewater for the urban areas of Lacey, Olympia, and Tumwater in Thurston County, Washington (at the southern end of Puget Sound). Since 2006, LOTT has also produced Class A reclaimed water at the Budd Inlet Reclaimed Water Plant (BIRWP) and Martin Way Reclaimed Water Plant (MWRWP) for irrigation and other non-drinking purposes. Some of the reclaimed water produced at the MWRWP is used to recharge (replenish) groundwater using rapid-infiltration basins at the LOTT Hawks Prairie Recharge Basins (Hawks Prairie site). Class A reclaimed water meets high water quality standards and is approved by the State Departments of Health and Ecology for many uses, including groundwater replenishment. Infiltration of reclaimed water at the Hawks Prairie site is permitted by the Department of Ecology.

LOTT chose to conduct the Study in response to community concerns about the safety of residual chemicals in reclaimed water. These concerns arose in part because the local climate differs from regions where much of the research related to these topics has previously been conducted. Developing a full understanding of the issue is important to LOTT, since the original long-range plan for meeting future wastewater needs includes expanding reclaimed water production and developing additional groundwater recharge facilities.

1.2 Study Purpose

The goal of the RWIS is to provide local scientific data and community perspectives to help policymakers make informed decisions about future reclaimed water treatment and uses. The primary study question was established as: “What are the risks from infiltrating reclaimed water into groundwater because of chemicals that may remain in the water from products people use every day, and what can be done to reduce those risks?” LOTT and the wider community will use the findings of the Study to inform future choices about water resource management and protection of public health and the environment.

2.0 Scope of Study

The RWIS is a “dual track” study involving science and community engagement. Public engagement helped identify key questions to address as part of the scientific effort, and fostered community conversations about future wastewater management options. The science portion of the Study focused on data gathering regarding the presence of residual chemicals and analyses of their fate and potential impacts in the environment.

2.1 Early Public Engagement

The RWIS began with an intensive scoping process that included active public engagement. A Community Advisory Group (CAG) was formed in 2012, consisting of local residents with diverse backgrounds and interests. This group was heavily involved in the scoping process, and has provided feedback and insights throughout the Study effort. Scoping was informed by public feedback gathered through stakeholder interviews, a phone survey, focus groups, and public workshops. Over 80 community questions about residual chemicals in reclaimed water were identified through these efforts. The questions fell into four main categories, which provided the framework for implementing the scientific study.

2.2 Study Structure

The RWIS was comprised of four primary tasks:

- Task 1: Water Quality Characterization – analyze groundwater, surface water, wastewater, and reclaimed water for residual chemicals and other water quality indicators.
- Task 2: Treatment Effectiveness Evaluation – examine how infiltrated reclaimed water interacts with soils and local groundwater, and what happens to residual chemicals over time in the environment.
- Task 3: Risk Assessment – identify the risk to human health (Task 3.1) and ecological health (Task 3.2) associated with infiltrating reclaimed water into groundwater.
- Task 4: Cost Benefit Analysis – determine the costs and benefits of various levels of treatment for reclaimed water and identify other strategies to address risks related to residual chemicals.

2.3 Study Management and Oversight

Several different groups and committees were involved in guiding and implementing the Study. The LOTT Board of Directors directed staff to conduct the Study and received regular Study updates. The LOTT Technical Sub-Committee (TSC), consisting of the Public Works Directors or designees for each of LOTT’s partner jurisdictions, as well as LOTT’s Executive Director, Operations & Facilities Director, and Engineering Director, served as the Steering Committee for the Study. A consultant team, led by HDR Engineering, Inc., provided the technical resources to implement Study activities. LOTT staff managed the effort and coordinated public engagement activities.

In addition to LOTT and HDR staff, three other groups provided oversight and input during the Study:

- An independent peer review panel (Panel), consisting of experts representing the fields of public health, toxicology, hydrogeology, and wastewater treatment, provided third party review throughout the Study. This group was organized and facilitated by the National Water Research Institute. The Panel met seven times throughout the course of the Study to provide comment on the scientific merit of task work plans, results, and reports. The Panel's findings and the project team's response to these were published as reports and are included as part of the Study's document archive.
- The Science Task Force (STF) included local scientific experts from the Cities of Lacey, Olympia, and Tumwater, Thurston County, Washington State Departments of Health and Ecology, and the Squaxin Island Tribe. The STF ensured that the Study took into account local scientific knowledge and concerns. This group provided frequent feedback throughout the study, from planning to results.
- The CAG members ensured that the Study answered questions important to the public, and that communication about the Study process and results could be easily understood. The CAG received updates and provided feedback on the Study at key junctures or milestones and their feedback was invaluable.

3.0 Water Quality Characterization (Task 1)

Task 1 of the study, completed in January 2017, characterized the types of residual chemicals present in LOTT's influent (untreated) wastewater, advanced secondary water treated at LOTT's Budd Inlet Treatment Plant (BITP), reclaimed water produced at the BIRWP and MWRWP, local area groundwater, and local area surface water. The results of Task 1 served as inputs to the later study tasks.

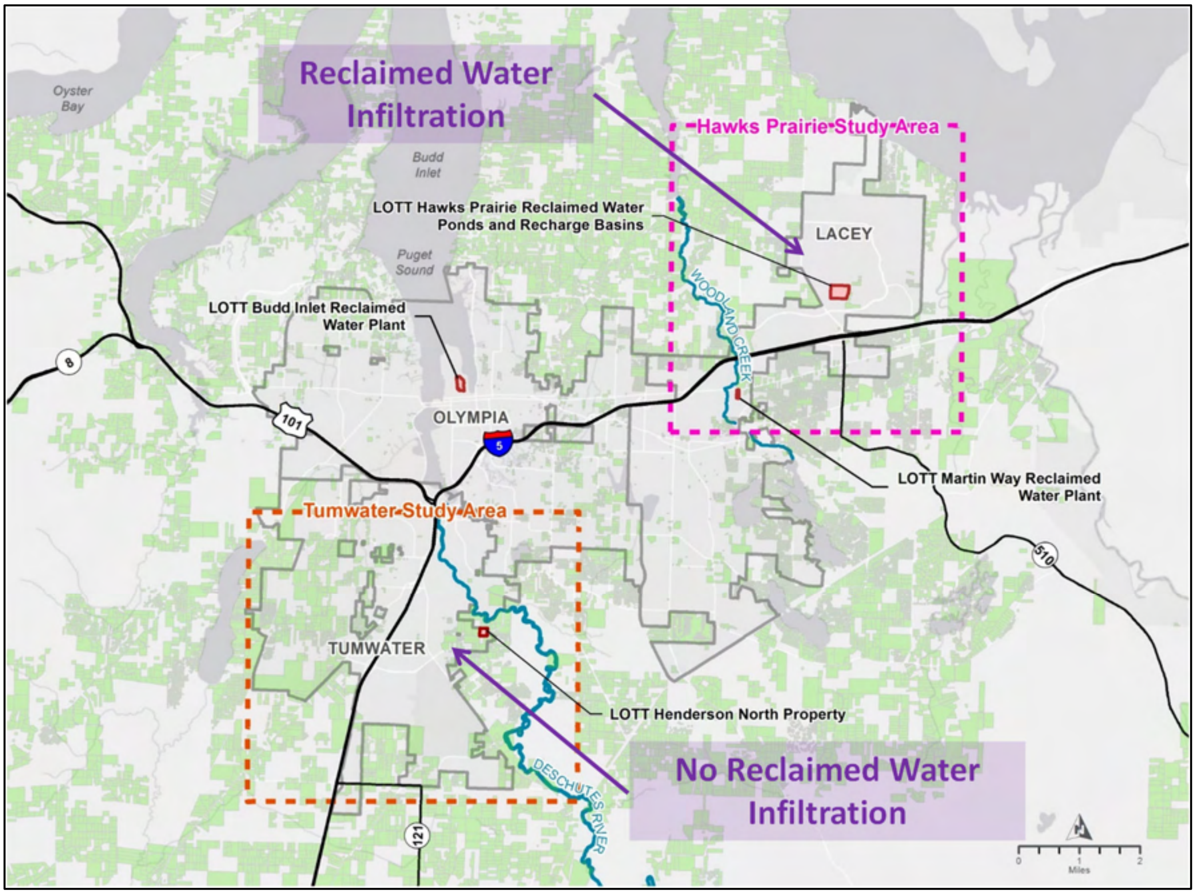
3.1 Study Area

Water quality sampling was conducted over the course of approximately one year, from November 2014 to December 2015, in two study areas, both approximately 16 square miles in size (see Figure 3-1):

- The Hawks Prairie Study Area is located in the vicinity of north Lacey, between Woodland and McAllister Creeks. LOTT's Hawks Prairie property is located within this study area. Infiltration of Class A reclaimed water has occurred in the recharge basins at this location since 2006.
- The Tumwater Study Area is located in the vicinity of Tumwater, between the Black and Deschutes Rivers. While reclaimed water has never been used for infiltration to groundwater within this study area, it is used for irrigation at several sites and LOTT may develop an infiltration site in this area in the future.

Both study areas are characterized as having residential and rural-residential land uses, with moderate commercial activity. Portions of each study area are sewered, while other portions are served by on-site septic systems (as indicated by the green shading in Figure 3-1). Drinking water comes from groundwater, provided to some residents by public supply wells and to others by individual residential wells. Wastewater generated in these areas and treated at LOTT's treatment facilities comes primarily from residential, commercial, and institutional (such as colleges, hospitals, and nursing homes) sources, with very few industrial inputs.

Figure 3-1. Study Areas



3.2 Monitoring Approach

The following water quality samples were obtained in these study areas:

- **Wastewater/Reclaimed Water**. Quarterly sampling of influent wastewater (wastewater coming into the plants prior to treatment) and treated reclaimed water was conducted at the BITP, BIRWP, and MWRWP, to identify residual chemicals present in LOTT's wastewater and reclaimed water, and to assess the effectiveness of treatment performance on these chemicals.
- **Groundwater**. Single samples were obtained from each of the following: 33 residential wells, 22 public supply wells, one spring, and one monitoring well. These samples were evenly divided between the two study areas. The intent was to obtain a characterization of groundwater quality across a wide geography, and in both shallow and deep aquifers.
- **Surface water**. A total of 44 samples at 12 discrete sites were obtained from Woodland Creek and the Deschutes River, and their tributaries, with an equal number of samples and sites in each of the study areas. Samples were obtained at various times of the year to assess variability under different flow conditions: two samples during late summer low-flow conditions, one sample after the first large fall storm, and one sample during winter high flow conditions.

For this task, water samples were analyzed for a range of water quality parameters regulated in drinking water and wastewater and for 129 unregulated residual chemicals found in household products, pharmaceuticals, and personal care products. Most of these have been reported at very low concentrations (on the order of parts per trillion, or nanograms per liter) in previous studies of treated wastewater, groundwater, and surface waters. While tens of thousands of such chemicals exist in commonly used products, the chemicals sampled for as part of this study were selected specifically to include those that are:

- Representative of large classes of compounds,
- Commonly detected in reclaimed water,
- Routinely used in the wastewater industry for evaluating treatment effectiveness and/or potential human or ecological health effects, and
- Reliably quantified in laboratory analysis

3.3 Water Quality Characterization Results

The results of the water quality characterization effort are described below.

3.3.1 General Water Quality

LOTT's two reclaimed water treatment facilities consistently produce high quality Class A reclaimed water that meets Washington State permit requirements with respect to conventional parameters, nutrient removal, and indicator bacteria reduction.

Groundwater quality was fairly consistent between the two study areas and reflected the general understanding of local area groundwater quality. For example, nitrate levels ranged from non-detect to 6.5 mg/L, with elevated concentrations observed mainly in areas served by residential on-site septic systems.

Surface water quality was consistent with characterizations in previous studies. In Woodland Creek, state surface water quality standards were met, with the exception of some dissolved oxygen, pH, and fecal coliform concentrations. In the Deschutes River watershed, State surface water quality standards were met, with the exception of low dissolved oxygen in Munn Lake, and high fecal coliform concentrations in Chambers and Percival Creeks.

3.3.2 Residual Chemicals in Wastewater and Reclaimed Water

The occurrence of residual chemicals in the influent wastewater and treated reclaimed water was fairly consistent between the two facilities, in terms of the chemicals observed most frequently and their concentrations. Of the residual chemicals analyzed, 88 were detected at least once in wastewater and 64 were detected at least once in reclaimed water. Figure 3-2 summarizes the number of residual chemicals detected at various detection frequencies, in both wastewater and reclaimed water. While LOTT's treatment processes are highly effective at removing common chemicals (such as acetaminophen, ibuprofen, triclosan, and caffeine) to levels below detection, fourteen residual chemicals were consistently detected in all eight samples taken of reclaimed water (four samples at each treatment facility). These fourteen chemicals are summarized in Figure 3-3, organized according to the level of removal achieved through LOTT's existing treatment processes.

Figure 3-2. Number of Residual Chemical Detections in Wastewater and Reclaimed Water

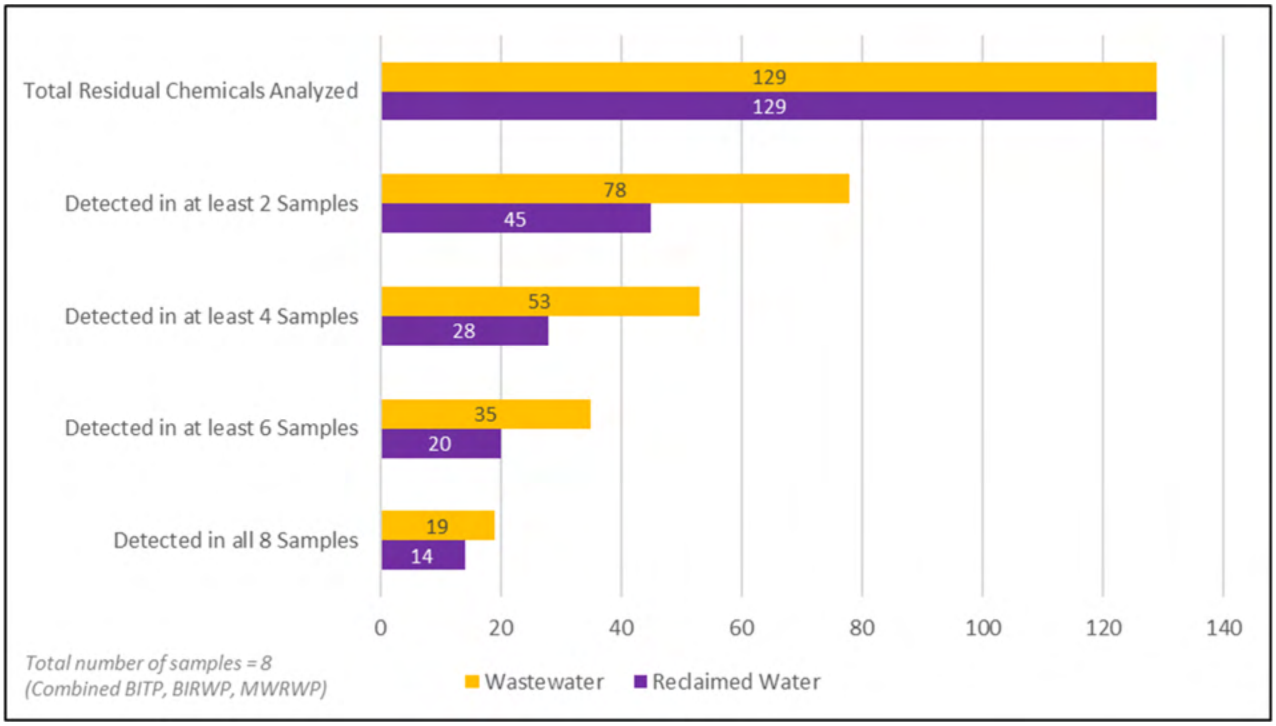
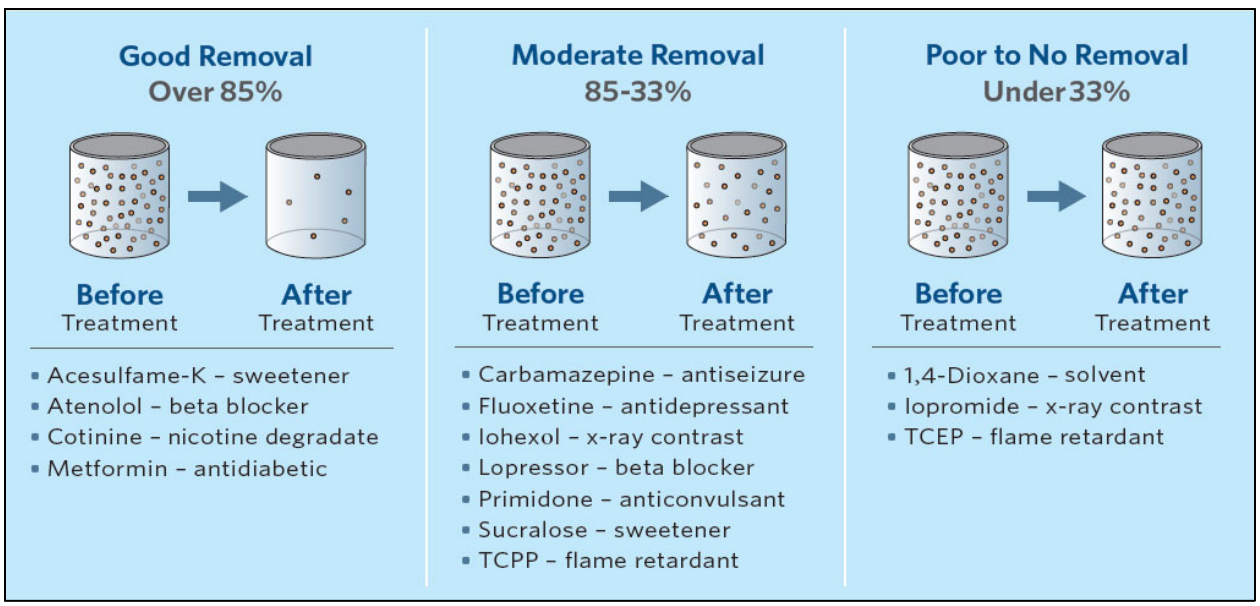


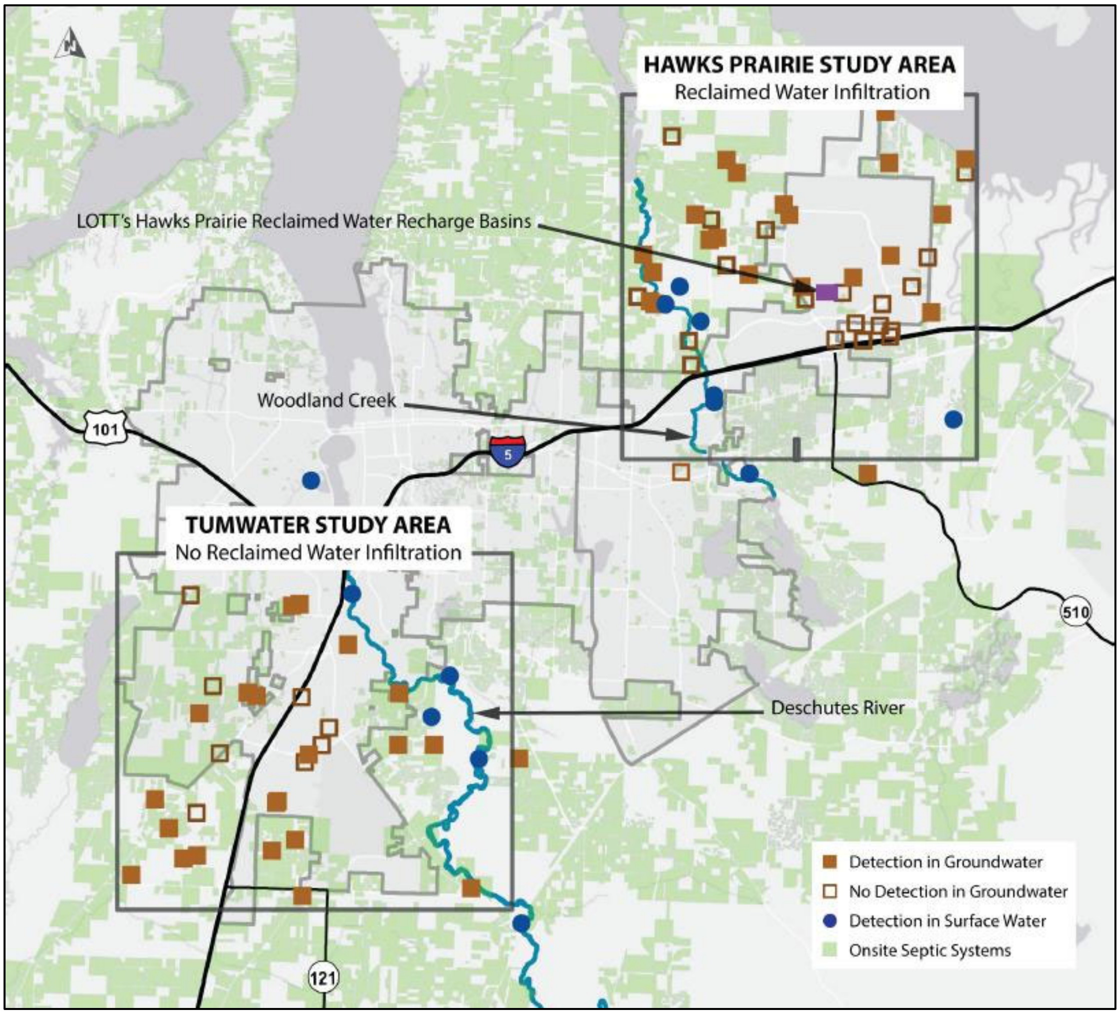
Figure 3-3. Treatment Effectiveness of the 14 Residual Chemicals Consistently Detected in Reclaimed Water



3.3.3 Residual Chemicals in Groundwater and Surface Water

Residual chemicals were detected in both groundwater and surface water throughout the two study areas, at lower frequencies and lower concentrations when compared with the residual chemicals observed in reclaimed water. Potential sources of residual chemicals present in the environment include septic systems, stormwater runoff, and reclaimed water (where it is utilized). Figure 3-4 identifies locations of residual chemical detections in the environment.

Figure 3-4. Residual Chemical Detections in Groundwater and Surface Water

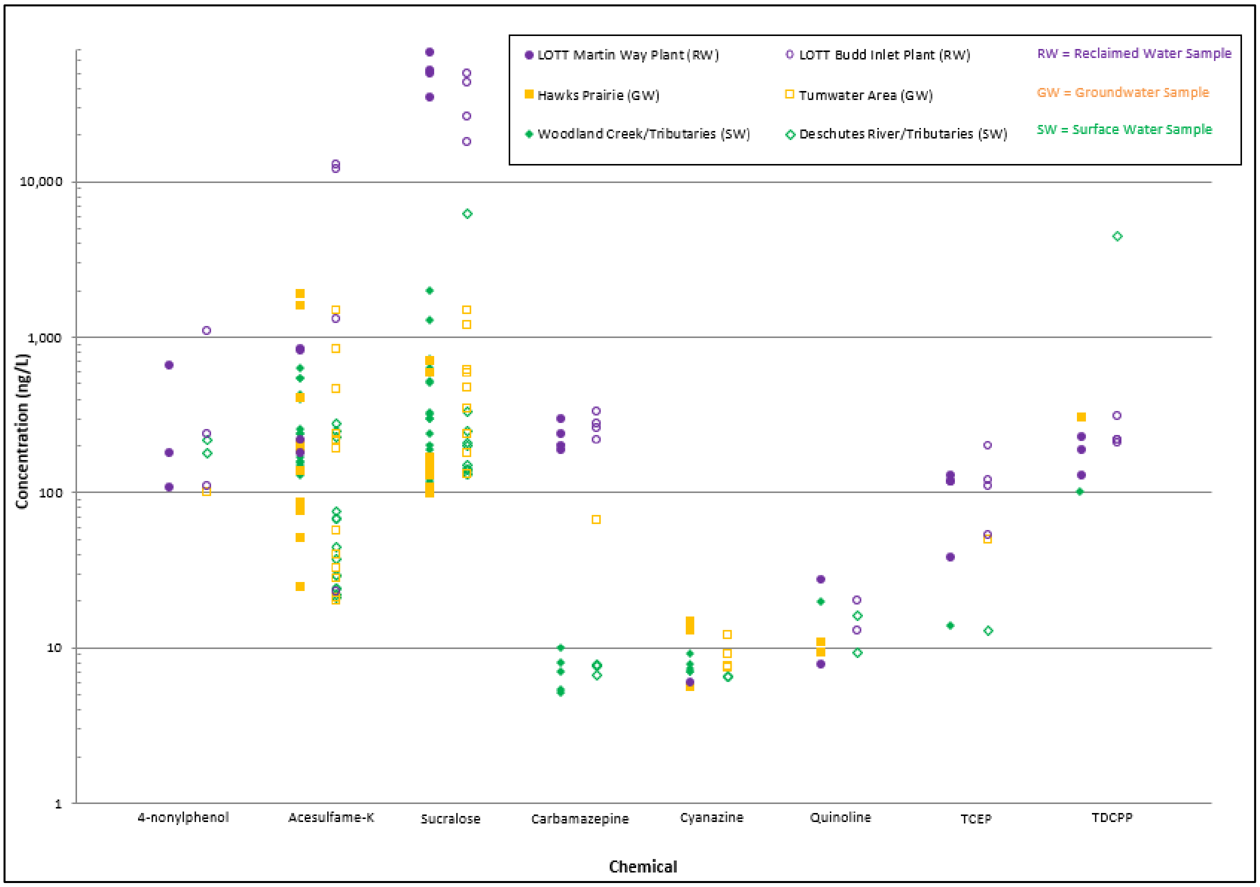


The residual chemicals most frequently detected in groundwater and surface water were the sweeteners acesulfame-K and sucralose. In groundwater these were detected 30 and 21 times (out of a total of 57 collected samples), at concentrations up to 1,900 and 1,500 ng/L, respectively. Similarly, in surface water, these sweeteners were detected 30 and 26 times (out of a total of 44 collected samples), at concentrations up to 630 and 6,300 ng/L, respectively. Other residual chemicals were found sporadically at low levels.

3.3.4 Comparison of Residual Chemicals Across All Sampled Waters

Eight residual chemicals were detected at least once in all three types of water: reclaimed water, groundwater, and surface water. Figure 3-5 depicts the ranges of concentrations observed for these chemicals.

Figure 3-5. Concentrations of Residual Chemicals Detected in Reclaimed Water, Groundwater and Surface Water



3.4 Water Quality Characterization Findings and Conclusions

LOTT's treatment processes are effective at removing many residual chemicals in wastewater, but some chemicals do remain after treatment. Of the residual chemicals analyzed, about 40% were detected in influent wastewater, and of those, about 40% were removed during treatment to non-detect levels. Only 14 were consistently observed in reclaimed water in all sampling events at both facilities, and of those, removal efficiency varied from good (>85%) to poor (<33%). The occurrence of observed residual chemicals in treated reclaimed water was fairly consistent at both facilities, in terms of the chemicals observed most frequently and their concentrations.

Residual chemicals were detected in groundwater and surface waters at concentrations lower than those observed in reclaimed water, and they were detected both in areas where groundwater infiltration of reclaimed water is occurring (Hawks Prairie/Woodland Creek) and where it is not (Tumwater Area/Deschutes River). Results of this study are comparable to those reported in 60 studies that were conducted elsewhere in the country and the world regarding the occurrence of residual chemicals in reclaimed water and the environment, and which were reviewed as part of the Study.

4.0 Treatment Effectiveness Evaluation (Task 2)

Task 2 of the study, conducted in 2018-2021, examined how infiltrated reclaimed water interacts with soils and local groundwater, and what happens to residual chemicals over time in the environment. This task is referred to as Treatment Effectiveness Evaluation due to the focus on evaluating the extent to which soil aquifer treatment might be at play after reclaimed water is infiltrated into the ground. This portion of the study was not intended to examine the degree to which wastewater or reclaimed water treatment processes remove residual chemicals – that was addressed as part of Task 1: Water Quality Characterization.

LOTT's Hawks Prairie site was used as the focus study site for Task 2, as groundwater recharge has been in operation at this location since 2006. The primary activities conducted in this task were characterization of local area hydrogeology, implementation of a tracer test to track movement of the infiltrated water, and hydrogeologic modeling to estimate chemical concentrations at various locations over time.

4.1 Hydrogeologic Investigation

Hydrogeologic conditions in the Hawks Prairie area have been previously characterized through multiple efforts carried out to support various objectives, including the permitting and design of the Hawks Prairie site in the early 2000's. From these previous characterizations, it is known that reclaimed water infiltrated at the Hawks Prairie site flows into the Vashon Advance Outwash (Q_{va}) aquifer underlying the site. This is referred to as the shallow aquifer in the Study. This aquifer is a large, regional aquifer composed of sand and gravel. It varies in thickness but the depth to the bottom of the aquifer is generally less than 150 feet below ground surface. The predominant groundwater flow direction in this aquifer is to the southwest. Some water moves from the shallow aquifer into a deeper aquifer, the Sea Level (Q_c) aquifer. This aquifer, also referred to as the deep aquifer in the Study, is comprised of coarse sand and gravel and is generally present at depths of 190 to 260 feet below ground surface. Groundwater movement in the deeper aquifer is generally to the east.

The Study built upon these prior characterizations to improve the understanding of the local area hydrogeology to a level of detail needed to support design of a tracer test and to refine an existing computer model of the area's hydrogeology.

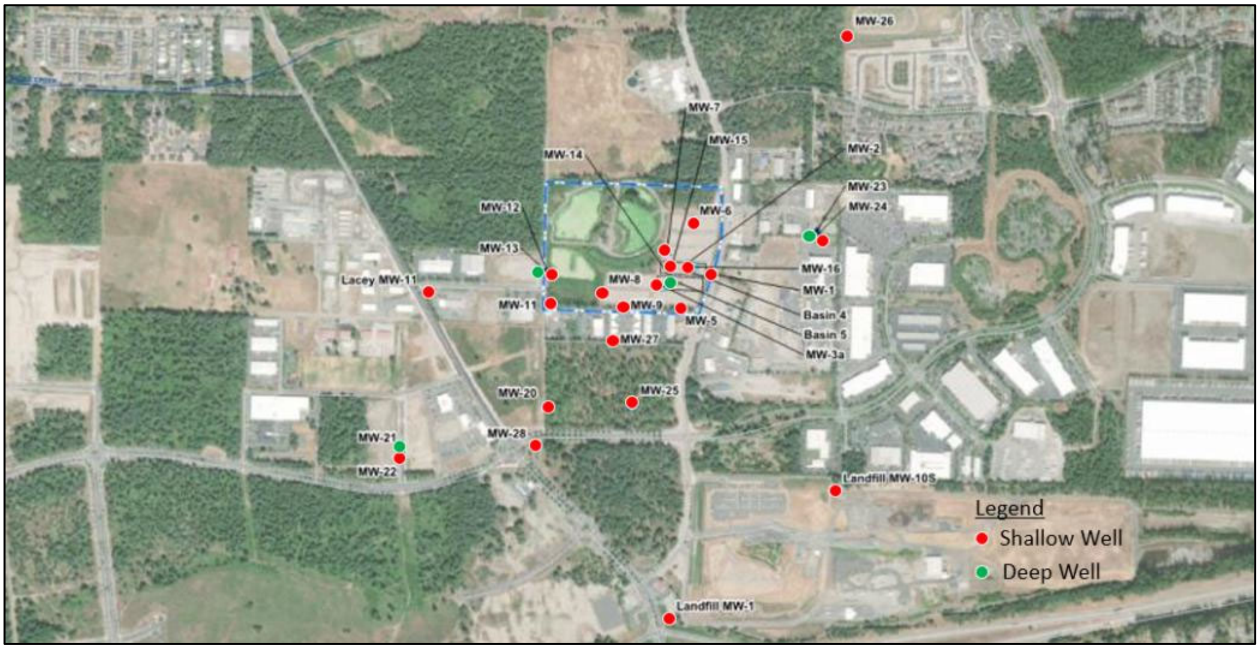
Field investigations were completed including drilling soil borings, collecting and analyzing soil samples, and installing monitoring wells on and around the LOTT Hawks Prairie property. Infiltration Basin #4 (Basin 4) was divided into half for its eventual use in the tracer test, and three lysimeters were installed in each half of the basin (six total lysimeters) at depths of 10, 25 and 50 feet. Instruments measuring soil moisture, conductivity, temperature and oxygen were also installed at the same depths adjacent to the lysimeters. Fourteen monitoring wells were installed; ten wells were completed within the shallow aquifer and four wells were completed in the deep aquifer. These wells were drilled on LOTT property, City of Lacey rights-of-way, and in some cases private property, for which legal agreements and decommissioning of the wells after completion of the monitoring was required. Groundwater levels were measured in all wells. Soil samples were collected and laboratory tested for a variety of hydraulic properties. *In-situ* aquifer testing was conducted including slug testing and aquifer pumping tests. This field work was completed from June through September 2017. Figure 4-1 and Figure 4-2 depict some of the field work that took place during this time.

The newly-installed lysimeters and wells, along with 29 existing wells owned by LOTT and others, were used to develop a comprehensive groundwater monitoring network to support the tracer test (see Figure 4-3).

Figure 4-1. Well Drilling at the Hawks Prairie Property

Figure 4-2. Photograph of Lysimeter Prior to Installation

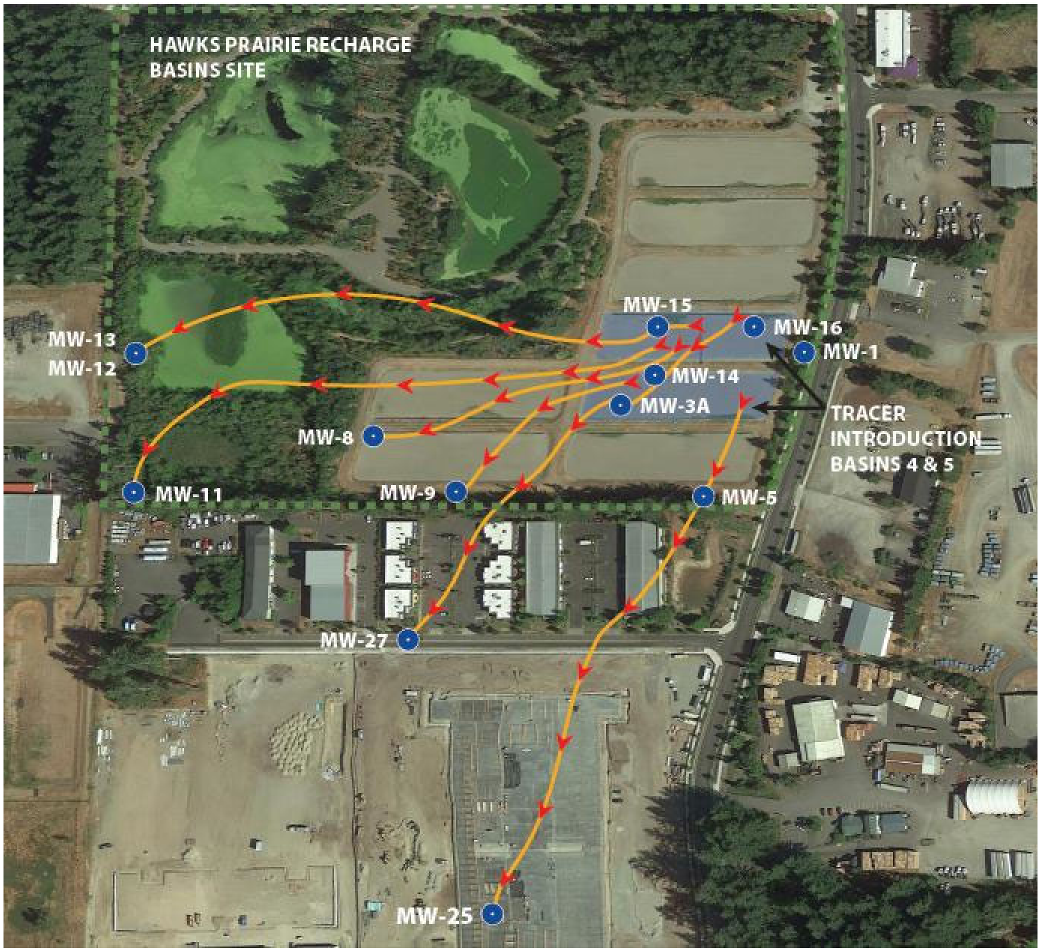
Figure 4-3. Monitoring Well Network



4.2 Tracer Test

With the monitoring network established, LOTT conducted a 10-month tracer test in 2018, to track the movement of reclaimed water and understand changes in residual chemical concentrations that take place within a half mile from the Hawks Prairie site. Two non-toxic, inert chemicals (potassium bromide and sulfur hexafluoride) were introduced to the reclaimed water entering Basins 4 and 5. Sampling data from 26 of the monitoring wells were used to characterize the flow direction and travel time of reclaimed water movement in groundwater away from the infiltration site. The tracer test data confirmed the general understanding that flow in the shallow aquifer at this location is generally to the south and west (see Figure 4-4).

Figure 4-4. Reclaimed Water Flow Directions (Shallow Aquifer)



Travel times vary widely as reclaimed water moves away from the site due to the heterogeneity of the hydrogeologic system, but in general it takes 30-40 days for reclaimed water to move from the infiltration basins through the unsaturated zone and into the shallow aquifer. Some reclaimed water advances into the deep aquifer in this time frame as well.

4.3 Water Quality Testing

During the tracer test, quarterly water quality samples were taken from reclaimed water, the lysimeters, and 13 of the monitoring wells to determine if and how water quality (and in particular, the concentration of residual chemicals) changes over time and distance from the point of recharge.

Data from the lysimeters and monitoring wells on the Hawks Prairie site indicate that water quality changes as reclaimed water moves through the unsaturated zone. Total organic carbon decreases by approximately 50% and biodegradable dissolved organic carbon decreases to below detection limits, providing evidence that soil aquifer treatment is at work with microorganisms breaking down organic material. Orthophosphate decreases by approximately 40%, indicating sorption of phosphorus to soil and aquifer material.

Many residual chemicals exhibited attenuation in concentration as a result of multiple mechanisms at work in the subsurface (dispersion amongst native groundwater, biodegradation, and sorption). An example of such attenuation is depicted in Figure 4-5, for the anti-epileptic medication carbamazepine. Figure 4-6 summarizes the level of attenuation for all residual chemicals that were consistently detected in reclaimed water during the tracer test. “Good” attenuation is defined as the chemical not being detected after approximately 30 days of travel time in groundwater, while “Poor” attenuation is defined as having multiple detections beyond 30 days of travel time.

Figure 4-5. Carbamazepine Concentration over Time in the Subsurface

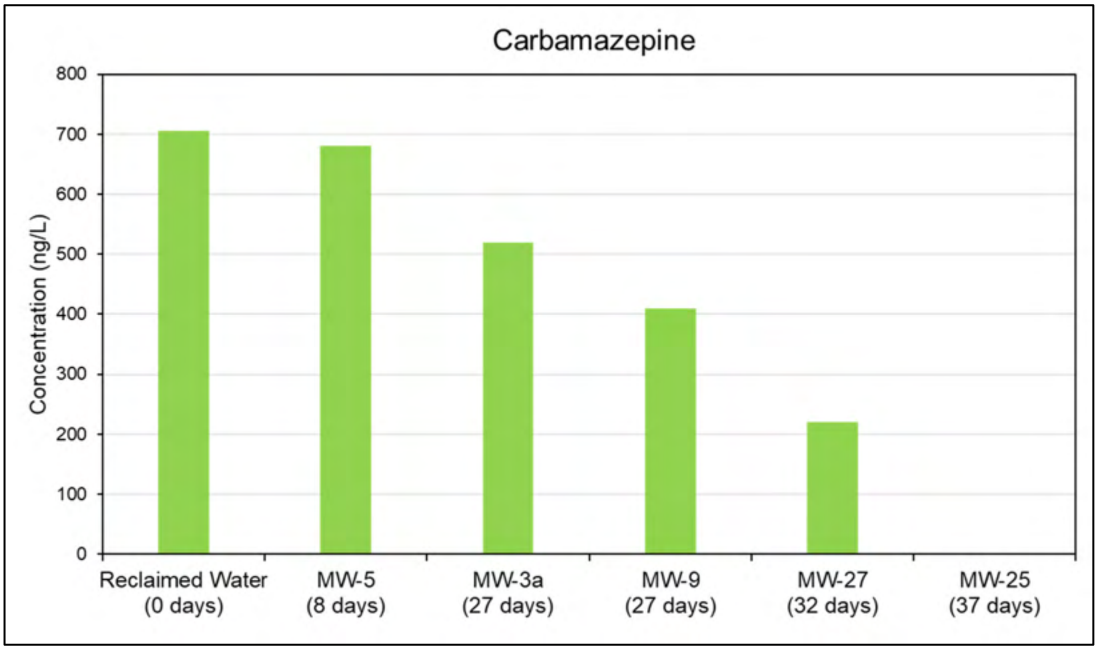
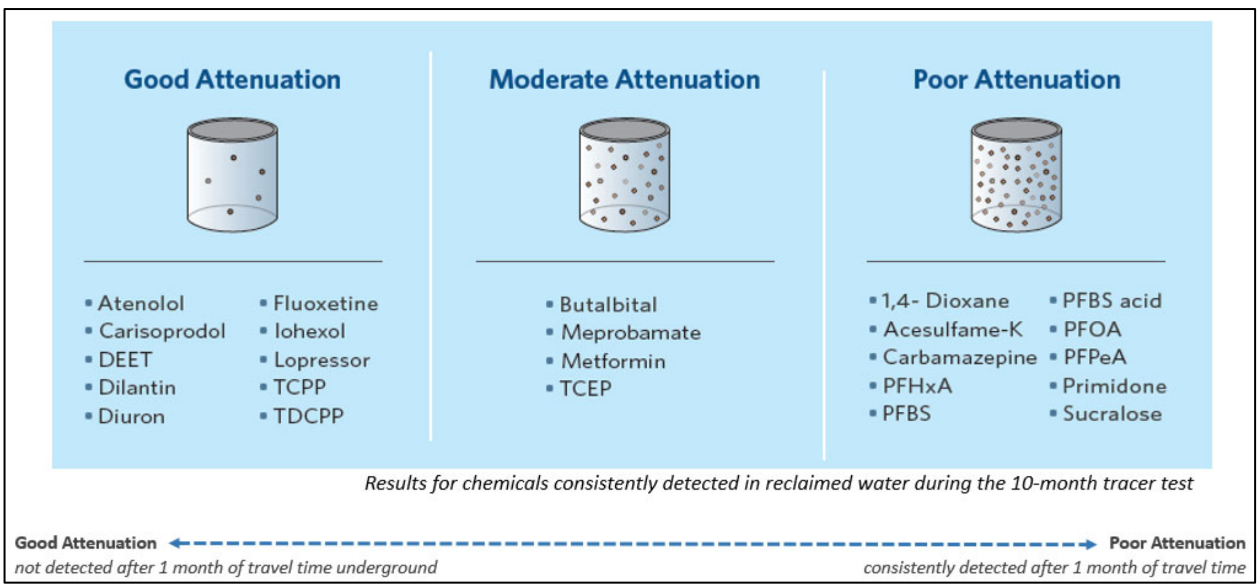


Figure 4-6. Residual Chemical Attenuation in Groundwater at Hawks Prairie



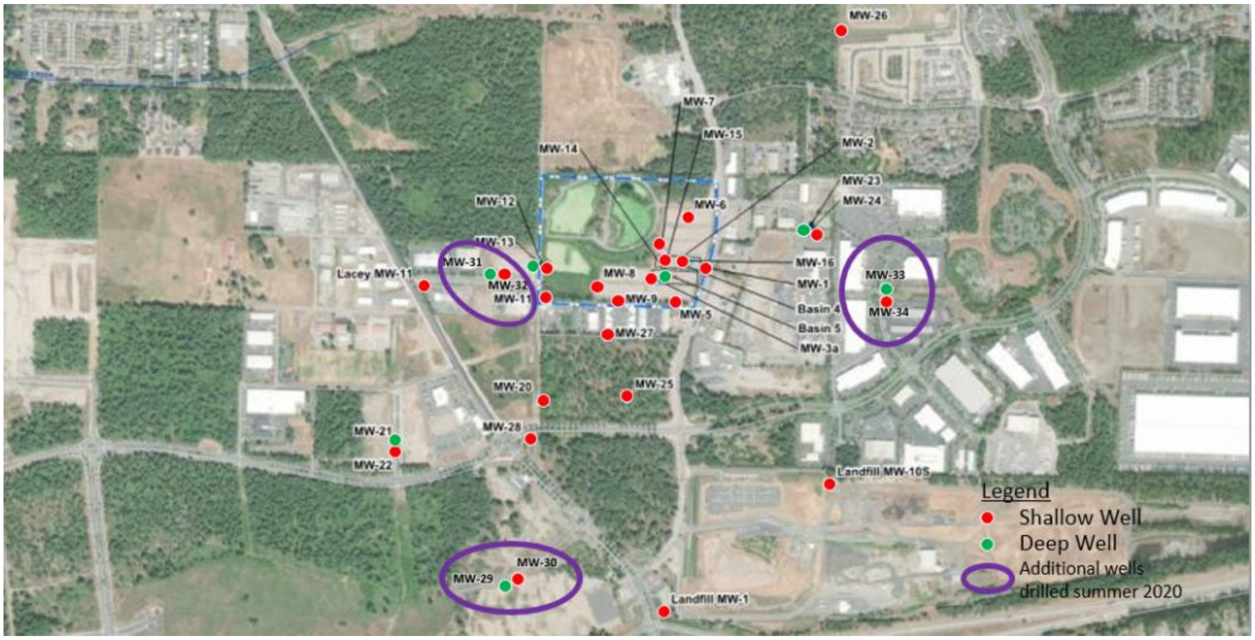
4.4 Groundwater Modeling

The results of the tracer test, as well as the increased understanding of the local area hydrogeology through the expanded monitoring well network, were used to update an existing hydrogeologic model to estimate reclaimed water flow paths and residual chemical concentrations within a 30 square mile area and out to 100 years into the future. The groundwater flow model platform of MODFLOW and the chemical fate and transport modeling platform of MT3DMS were used to conduct this work.

Figure 4-7. Computer Modeling of Groundwater

Preliminary model results generated in late 2019 and early 2020 yielded findings that were not fully anticipated, in terms of movement of reclaimed water between the shallow and deep aquifers, and the direction of flow in the portion of the deep aquifer in the vicinity of the Hawks Prairie property. To fill data gaps in the hydrogeologic knowledge of localized areas surrounding the Hawks Prairie site, six additional wells were drilled in 2020, primarily to increasethe understanding of the connectivity between the shallow and deep aquifers in this area (see Figure 4-8).

Figure 4-8. Additional Monitoring Well Locations



This information confirmed that the thickness of the geologic unit that separates the shallow and deep aquifers (i.e., the "Kitsap Formation") decreases significantly to the south of the Hawks Prairie site and is likely absent in some locations. This leads to movement of reclaimed water from the shallow aquifer to the deep aquifer. The new wells also confirmed flow direction of the deep aquifer to the east.

The groundwater model was then calibrated to conditions observed from the field investigations (e.g., groundwater elevations) and the tracer test (e.g., travel times of the tracers), and used to estimate the extent of reclaimed water movement over a 100-year period from present day. An initial transient flow simulation was first used to reflect historical annual average recharge rates from 2006 to 2020 (ranging from 0 to 0.99 mgd), to characterize the extent of reclaimed water movement by 2020. A second transient simulation incorporated anticipated increases in recharge rates to reflect planned growth in LOTT's service area. Projected annual average flow rates were increased from 0.5 mgd in 2020 to 4.2 mgd by 2120. Sensitivity analyses were also performed to evaluate the variability in the key model elements of dispersion, porosity, and recharge, the latter being explored to understand potential impacts of climate change and development upon future groundwater conditions. The modeled extent of reclaimed water movement in the shallow aquifer is depicted in Figure 4-9, wherein the color depicts the portion of groundwater at a given location that is comprised of water that originated as reclaimed water infiltrated at the Hawks Prairie site. This is characterized as a ratio shown as C/C_o (see Section 4.5 for further definition). The values of this ratio range from 0 (the white fringe, indicating essentially no presence of water infiltrated at the Hawks Prairie site) to 1 (the dark blue, indicating groundwater is comprised fully of water that was infiltrated at the Hawks Prairie site).

Figure 4-9. Modeled Extent of Reclaimed Water Movement (2020 and 2120; Shallow Aquifer)

4.5 Exposure Point Concentrations

The groundwater model was an important tool used in determining Exposure Point Concentrations (EPCs), which are the concentrations of residual chemicals at locations where people or wildlife may be exposed through contact with groundwater (e.g., through well water) or surface water (e.g., through the connectivity of groundwater with Woodland and McAllister Creeks). Multiple factors were considered when deriving EPCs. The following equation summarizes how an EPC was determined for a particular chemical for a specific amount of travel time away from the point of infiltration:

$$EPC = (C_{ochem} * C/C_o) * (1-(AF * T_{loc}))$$

Where:

C_{ochem}	= the concentration of the residual chemical in reclaimed water
C/C_o	= the influence of dispersion at a particular exposure point (i.e., the percent of original chemical concentration remaining after the effects of dispersion, as depicted in Figure 4-9)
AF	= the calculated attenuation factor
T_{loc}	= the model predicted travel time to the exposure point

The "starting point" of the EPC calculation is the reclaimed water concentration of each assessed residual chemical, which was determined based on all reclaimed water monitoring data obtained during Tasks 1 and 2. Where data were sufficient for statistical analysis, the reclaimed water concentration was calculated as the 95% upper confidence limit (UCL) of the arithmetic mean of the available data set, using U.S. EPA's ProUCL software. Where data were not sufficient for this approach, the observed maximum reclaimed water concentration was used.

Computer modeling was then used as a key step in defining the extent to which concentrations decrease due to dispersion. Further reductions in chemical concentrations in the groundwater environment were characterized where empirical data from the tracer test and water quality monitoring strongly indicated additional attenuation beyond dispersion for a particular chemical. In these cases, an "attenuation factor" was derived that accounts for the added effects of mechanisms such as biodegradation and sorption.

The EPC calculation incorporated an attenuation factor for nine chemicals, but it was based solely on model-derived dispersion for the other chemicals evaluated. The EPCs were then used as inputs into the risk assessments conducted at part of Task 3.

4.6 Treatment Effectiveness Findings and Conclusions

Extensive hydrogeologic characterization, made possible by the installation of lysimeters and new groundwater monitoring wells at and near the Hawks Prairie site, along with a 10-month long tracer test yielded an increased understanding of subsurface conditions. Reclaimed water infiltrated in this area flows generally southwest in the shallow aquifer. The geologic unit that separates the shallow aquifer from the deep aquifer in this area has segments that are thin or absent, which allows for movement of reclaimed water into the deep aquifer, at which point it then generally flows to the east.

Most residual chemical concentrations decrease with time and distance as reclaimed water mixes with groundwater and moves away from the site. Of the 24 residual chemicals detected during all quarterly sampling events as part of the 10-month tracer test, ten exhibited “good” attenuation in groundwater, meaning they were not detected after 30 days of travel time. The remaining residual chemicals were detected at least once beyond that time of travel.

EPCs were determined for the residual chemicals of interest in the risk assessments. These values represent the concentrations of chemicals predicted to be present either now or within the 100-year future at locations where people or wildlife may come into contact with reclaimed water after it has mixed with groundwater. The EPCs for some residual chemicals are solely a function of dispersion, as the chemicals are resistant to further attenuation by biodegradation and sorption, while the EPC calculations for nine chemicals included additional attenuation due to these factors, based on empirical evidence gathered during the Study. This information provided key inputs to the Task 3 risk assessments.

5.0 Human Health Risk Assessment (Task 3.1)

A human health risk assessment (HHRA) was conducted, in accordance with U.S. EPA guidance, to characterize the potential risk to human health by residual chemicals detected in reclaimed water that is used to recharge groundwater. Before risk could be calculated, average daily doses of each chemical of interest were estimated for different hypothetically exposed populations, representing a range of exposure scenarios. Based on these dose estimates, quantitative estimates of the potential for adverse health effects to exposed populations were derived. Potential adverse effects considered in the HHRA include noncancer hazards and lifetime excess cancer risks.

5.1 Screening Level Evaluation

In an initial screening-level evaluation, concentrations of 84 residual chemicals detected in at least one water sample during Tasks 1 and 2 were “screened” to identify those that might present health risks that exceed U.S. EPA’s allowable risk range to people who contact the water. In the screening-level evaluation, maximum-detected concentrations of the chemicals in reclaimed water were compared to toxicity benchmark concentrations, termed Drinking Water Equivalent Levels (DWELs). DWELs were set equal to existing federal or state water quality standards or toxicity criteria, or derived from published toxicological data or therapeutic doses (for pharmaceuticals).

The screening-level evaluation showed that 15 chemicals were detected at least once in reclaimed water at a concentration in excess of their DWEL. Because this list included four hormones and two per- and polyfluoroalkyl substances (PFAS), all other hormones and PFAS analyzed in the Study were also selected for further evaluation in the HHRA, as were 14 additional chemicals that were detected at a maximum concentration of 10% or more (i.e., within one order of magnitude) of their DWEL. Overall, a total of 44 chemicals was selected for further evaluation in the HHRA.

5.2 Chemicals of Interest

In the next step of the risk assessment, exposure point concentrations (EPCs) were used to refine the list of chemicals of interest. People living downgradient of LOTT’s infiltration basins do not have direct contact with reclaimed water and will not have direct contact in the future. Further, chemicals in the reclaimed water that undergo subsurface transport through groundwater will be subject to several processes, including advection, dispersion, diffusion, sorption, and decay, that affect the concentration and location of each constituent, resulting in attenuation of downgradient concentrations prior to points where exposure could occur. To account for the impact of these processes on potential residual chemicals in downgradient well water or surface water, the list of chemicals considered in the HHRA was further refined by comparing estimated EPCs of each chemical to the DWELs. If the maximum-estimated EPC of a chemical was equal to or greater than 10% of the chemical’s DWEL, the chemical was retained for more detailed evaluation in the HHRA. If the chemical was never detected in monitoring, it was not included in the HHRA.

Based on these comparisons, eight chemicals of interest (COIs) were retained for further evaluation in the HHRA. These COIs are:

- 1,4-Dioxane (an industrial chemical with widespread use as a stabilizer in certain chlorinated solvents, paint strippers, greases, and waxes)
- Carbamazepine (a pharmaceutical used to treat certain types of seizures such as epilepsy, and typically classified as an anticonvulsant)
- N-Nitroso dimethylamine (NDMA) (a chemical that was formerly used in the production of rocket fuel, antioxidants, and softeners for copolymers and that is currently used for research purposes, but is also produced as a byproduct of water chlorination disinfection processes undertaken at some water treatment facilities; it also occurs in some cosmetics and other products and is produced in the human body from nitrosamines and nitrates present in foods such as smoked or cured meats and fish, dried milk and formula, and vegetables, and in beverages such as beer and whiskey)
- Perfluoro octanoic acid (PFOA), perfluoro-n-hexanoic acid (PFHxA), and perfluoropentanoic acid (PFPeA) (three members of a class of human-made compounds known as PFAS that have been used in surface coating and protectant formulations because of their unique surfactant properties, including in paper and cardboard packaging products, carpets, leather products, textiles, firefighting foams, and nonstick coatings)
- Primidone (a pharmaceutical used to treat seizure disorders and typically classified as an anticonvulsant)
- Quinoline (an industrial chemical used mainly as an intermediate in the manufacture of other products, and also as a catalyst, corrosion inhibitor, preservative for anatomical specimens, and solvent for resins and terpenes, as well as in metallurgical processes, dye manufacture, and production of polymers and agricultural chemicals).

5.3 Exposure Scenarios

In the HHRA, potential exposures to hypothetical future populations that could be exposed to COIs in tap or well water or in surface water in Woodland Creek or McAllister Creek were quantified using U.S. EPA recommended risk assessment methodologies. Several scenarios and populations were selected to represent a range of potential exposures. The scenarios and populations evaluated in the HHRA are:

- Residents (child and adult) exposed directly to potable water from domestic water supply wells via ingestion and dermal contact, and that could be exposed via inhalation of volatiles from the water into the domestic living space. For these populations, both a reasonable maximum exposure (RME) (defined as an upper bound estimate of exposure to a resident that could reasonably be expected to occur via a given exposure pathway) and a more likely exposure (MLE) (defined as an estimate of an “average” level of exposure to a resident that could reasonably be expected to occur via a given exposure pathway) are evaluated.
- Maintenance/landscape workers (adult) exposed to tap or well water via direct ingestion and dermal contact (e.g., while irrigating at a park or golf course).

- Recreators (child) exposed to tap or well water at a recreational water feature through dermal contact and incidental ingestion as well as through direct ingestion of tap water while engaging in play (e.g., at a playground or ball field).
- Recreators (child and adult) exposed to surface water in Woodland Creek or McAllister Creek through dermal contact and incidental ingestion during playing, fishing, wading, or swimming.
- Fish consumers (child and adult) who eat fish caught in Woodland Creek or McAllister Creek.

Exposures to these populations were estimated using EPCs determined in the Task 2 fate and transport modeling and exposure parameters that describe behavioral characteristics and physiological characteristics representative of the populations of interest. For most exposure parameters, characteristics descriptive of U.S. populations or U.S. EPA standardized default exposure parameters for characterizing reasonable maximum exposures were used. As appropriate, locally relevant information and/or professional judgment was also applied. Characteristics used in the calculation included factors such as quantity of water ingested, body weight, and number of years living in the home.

Potential EPCs of COIs in tap or well water were based on the maximum-estimated concentrations in the shallow and deep aquifers which, for all COIs, were estimated to occur at a location 200 feet downgradient of the discharge basins (the closest location for which concentrations were modeled). While no domestic or municipal water supply wells are currently located this close to the recharge basins, it is assumed that 200 feet represents the minimum buffer that would be required in future permitting to install a new groundwater supply well in proximity to an infiltration basin. Use of EPCs estimated at 200 feet downgradient is assumed to provide a conservative (health-protective) estimate of potential exposures to future downgradient populations.

For those chemicals estimated to infiltrate from the aquifers to points of entry into each creek, EPCs were estimated assuming that concentrations in the aquifers at points of entry are reduced by mixing with flow within each creek.

For the exposure populations and scenarios, doses in units of milligrams per kilogram body weight per day (mg/kg-d) were estimated for each pathway (ingestion and dermal) and COI using assumed exposure parameters and EPCs. For evaluation of noncarcinogenic effects, doses were averaged over one year and presented as annual average daily doses (ADDs). For evaluation of cancer risk, doses were averaged over a lifetime (assumed to be 70 years) and presented as lifetime average daily doses (LADDs). These dose estimates were then combined with chemical- and pathway-specific noncancer or cancer toxicity criteria to derive estimates of noncancer hazard and cancer risk associated with the exposures.

The impacts to calculated risks of reducing residual chemical concentrations through additional levels of advanced reclaimed water treatment were also identified.

5.4 Human Health Risk Assessment Results

The potential for noncarcinogenic health effects was evaluated using a hazard index (HI) approach. This approach assumes that for a particular exposure scenario, simultaneous exposures of a person to a chemical via several pathways is additive, and that the relative magnitude of the adverse effect associated with the total exposure to that chemical is proportional to the summed ratios of pathway-specific exposures to allowable exposures. The results of the HHRA predicted the following with regard to noncancer hazards under the current reclaimed water treatment scenario:

- Estimated upper bound noncancer HIs exceed the minimum threshold level of concern of 1.0 for only one chemical and scenario—PFPeA for the RME child resident scenario, with an estimated HI of 1.3 (or 1 if rounded to one significant figure). The RME scenario is intended to reflect a high end estimate of potential exposures. It is defined as the highest exposure that is reasonably expected to occur at a site, and is intended to estimate a conservative exposure case (i.e., well above the average case) that is still within the range of possible exposures, e.g., within approximately the 90th to 99.9th percentiles of the risk distribution for an exposure scenario.
- An HI >1 does not mean that adverse health effects are expected or will occur. In fact, if the noncancer HI is close to 1 (as is the case for the upper bound noncancer hazard estimate for the RME child resident scenario for PFPeA), adverse health effects are unlikely even if a person's exposure is at this estimated upper bound level. This is because multiple uncertainty factors are incorporated into the derived toxicity criterion (i.e., allowable daily dose) used to calculate the noncancer hazard for this chemical.
- Estimated upper bound noncancer HIs for PFPeA for the shallow and deep aquifers are nearly the same because the estimated EPCs for these aquifers are nearly the same (with the EPCs for the deep aquifer slightly lower).
- For the RME resident scenarios, estimated noncancer HIs for a child are approximately two times those for an adult. This is because HIs are determined based on an estimated annualized average daily dose and typically, the average intake of a child on a per kilogram of body weight basis is greater than that of an average adult. The estimated upper bound noncancer HI for the RME adult resident scenario is below 1.0.
- Greater than 99% of the estimated noncancer HIs for the RME child or adult resident scenarios for PFPeA are contributed by the water ingestion pathway. This pathway assumes a child drinks approximately 1 liter of water per day or an adult drinks approximately 2.6 liters of water per day, nearly every day (350 days per year) in the home. The contribution of dermal contact with water to total daily dose is <1%.
- Estimated noncancer HIs for all other chemicals and all other scenarios, including the MLE resident scenario, are below 1.0. Under the MLE resident scenarios, the rate of ingestion of tap water in the home is assumed to be approximately one-half liter per day for a child and 1.3 liters per day for an adult for 234 days per year (approximately two-thirds of a year).

- People can also be exposed to PFPeA in the diet. Estimated daily exposures for the RME resident from tap water are estimated to be comparable to exposures from the diet unrelated to potential reclaimed water sources.

The potential for cancer-related risks was evaluated by comparing estimated lifetime excess cancer risks (LECRs) to established benchmarks. With regard to predicted cancer risks under the current treatment scenario, the following was found:

- Estimated upper bound LECRs exceed the *de minimis* cancer benchmark of 1 in 1,000,000, or 10^{-6} for only one chemical and scenario—NMDA for the RME resident scenario, which has an estimated LECR of 2.9×10^{-6} (3×10^{-6} if rounded to one significant figure).
- This LECR can be interpreted as a probability that, at the upper bound of the risk estimates, 2.9 persons in one million (10^{6}) people could develop cancer if they are exposed to this chemical at this rate over their lifetime.
- While the upper bound LECR estimate for the RME resident scenario slightly exceeds a *de minimis* one-in-a-million LECR, it falls within the range of risks considered to be allowable by U.S. EPA and others at different sites depending on specific site characteristics (1×10^{-4} to 1×10^{-6}, or 1 in 10,000 to 1 in 1,000,000).
- Estimated upper bound LECRs for NDMA for the shallow and deep aquifers are nearly the same because the estimated EPCs for these aquifers are nearly the same (with the EPCs for the deep aquifer slightly lower). More than 99% of this estimated risk is contributed by the water ingestion pathway.
- Estimated LECRs for all other chemicals of interest and exposure scenarios, including the MLE resident scenario, are below the level of concern of 1×10^{-6}.
- Other sources of exposure to NDMA include food or beverages that contain nitrosamines, such as smoked or cured meats and fish, vegetables, dried milk or formula, and malt beverages (“exogenous” NDMA) and food that contains nitrates, such as cured meats or fish and vegetables, that can be converted to NDMA in the stomach (“endogenous” NDMA). Estimated upper bound daily exposures for the RME resident from tap water are estimated be about 1 to 3% of exposures to exogenous or endogenous NDMA from sources unrelated to potential reclaimed water sources.

With regard to potential noncancer hazards and cancer risks associated with consumption of fish from either McAllister Creek or Woodland Creek, the HHRA predicts that even at a high end fish consumption rate of 330.5 grams per day (g/d) (corresponding to the 95th percentile estimate of “total fish” consumption from the Puget Sound and elsewhere by Squaxin Tribe consumer only adults, as presented by U.S. EPA and supported by the Squaxin Tribe, or approximately 609 servings per year assuming an average 7-ounce serving size), estimated noncancer hazards and cancer risks for these scenarios are below threshold levels of concern.

A probabilistic risk assessment (PRA) was conducted for the two chemicals with upper bound hazard or risk estimates that slightly exceed risk thresholds based on the deterministic risk assessment—PFPeA and NDMA, for the RME resident scenario. The PRA results indicated that estimated HIs for PFPeA and LECRs for NDMA meet the human health protection goals set by the Florida Department of Environmental Protection and the Oregon Department of

Environmental Quality (the only two regulatory agencies with PRA-based water quality goals corresponding to specific distribution percentiles for HIs and LECRs). Moreover, even at the 99th percentile, the LECRs for NDMA are within U.S. EPA's allowable risk range ($1×10^{-6}$ to $1×10^{-4}$).

Two key sources of uncertainty in the PRA noncancer hazard and cancer risk estimates for PFPeA and NDMA are the assumed water concentrations and the applied toxicity criteria. Water concentrations applied in the PRA are point estimate values and are the same as values used in the deterministic HHRA. They are based on the modeled chemical concentration in the shallow or deep aquifers 200 feet downgradient of the basins, using the 95 percent upper confidence limit (UCL) of the arithmetic mean concentrations of these chemicals in reclaimed water as the initial concentration. For these chemicals, no biodegradation or sorption downgradient of the source was assumed to occur. Overall, these assumptions are assumed to result in conservative (health protective) estimates of potential EPCs for these chemicals. The toxicity criteria used to estimate noncancer hazards or cancer risk for these chemicals are the same as applied in the deterministic HHRA and are assumed to provide a conservative (health protective) estimate of potential hazards or risks at a given dose. Thus, even if exposures consistent with the upper bounds of the PRA output distributions were to occur, it does not mean that adverse health effects are expected or will occur.

5.5 Human Health Risk Assessment Findings and Conclusions

The key findings of the HHRA are:

- Estimated upper bound noncancer hazard indices (HIs) exceed the minimum threshold level of concern of 1.0 for only one chemical and scenario—PFPeA for the RME child resident scenario, with an estimated HI of 1.3.
- Estimated upper bound lifetime excess cancer risks (LECRs) exceed the *de minimis* cancer benchmark of 1 in 1,000,000, or 10^{-6} for only one chemical and scenario—NDMA for the RME resident scenario, which has an estimated LECR of $2.9 × 10^{-6}$.

A probabilistic risk assessment (PRA) conducted for PFPeA and NDMA indicated that estimated HIs for PFPeA and LECRs for NDMA meet the human health protection goals set by the Florida Department of Environmental Protection and the Oregon Department of Environmental Quality (the only two regulatory agencies with PRA-based water quality goals corresponding to specific distribution percentiles for HIs and LECRs).

Two key sources of uncertainty in this analysis are the assumed water concentrations and the applied toxicity criteria. For both parameters, assumptions are conservative (health protective) in nature. Thus, even if exposures consistent with the upper bounds of the PRA output distributions were to occur, it does not mean that adverse health effects are expected or will occur.

6.0 Ecological Risk Assessment (Task 3.2)

An ecological risk assessment (ERA) was conducted to assess the potential risk posed by residual chemicals to aquatic-dependent organisms that utilize streams fed in part by groundwater influenced by reclaimed water.

The ERA was prepared in accordance with U.S. EPA guidance. Chemicals of potential ecological concern (COPECs) were initially identified through a screening-level evaluation. The list of COPECs was refined using data from the Task 2 analysis, and a final list of five COPECs was evaluated in detail in an exposure analysis that characterized potential effects and risk. The ERA found that the use of reclaimed water for groundwater recharge does not pose unacceptable risk to aquatic-dependent organisms.

6.1 Problem Formulation

The first phase of the ERA, the problem formulation, was conducted in 2019–2020. The problem formulation included a site description for the two waterbodies of interest (Woodland and McAllister Creeks), selection of receptors of concern (ROCs), development of a conceptual site model (CSM), identification of assessment and measurement endpoints, and identification of COPECs.

ROCs for Woodland and McAllister Creeks include the general aquatic community that may be exposed to residual chemicals via direct contact with surface water (e.g., aquatic plants, invertebrates, fish, and herptiles), as well as fish and aquatic-dependent wildlife that may feed in Woodland and McAllister Creeks. Belted kingfisher and northern river otter were selected as ROCs to represent piscivorous species of birds and mammals, respectively.

The CSM describes pathways through which ecological receptors may be exposed to residual chemicals and identifies assessment endpoints and risk questions to evaluate those endpoints. The most significant pathways evaluated in the ERA are direct exposure to surface water, exposure of fish from bioaccumulation of chemicals in tissue, and exposure through ingestion of fish tissue containing bioaccumulated chemicals. The protection and maintenance of aquatic communities, fish populations, and aquatic-dependent bird and mammal populations were the ecological assessment endpoints (EAEs) evaluated. Risk questions and measurement endpoints were developed for all ROCs based on the complete and significant exposure pathways for surface water and fish tissue (for addressing risk to both fish and ROCs consuming fish) identified in the CSM.

COPECs were identified by comparing the maximum concentrations of residual chemicals to conservative screening benchmarks for water. In addition, each chemical was evaluated for persistence and bioaccumulation potential based on half-lives and bioaccumulation factors, respectively. Chemicals were identified as COPECs if concentrations were greater than the screening benchmarks, or if a chemical was classified as potentially highly persistent and bioaccumulative.

6.2 Groundwater Modeling and COPEC Refinement

A groundwater fate and transport model was developed to estimate concentrations of COPECs discharging to Woodland and McAllister Creeks over the course of 100 years of reclaimed water infiltration, beginning from present day. The model output was used to refine the list of COPECs identified in the screening evaluation. For example, chemicals were removed from the list of COPECs if EPCs for both creeks were zero or if EPCs were less than the screening benchmark. Five COPECs were ultimately identified for quantitative risk evaluation: the surfactant 4-nonylphenol and four PFAS (perfluoro-1-butanesulfonic acid [PFBS], perfluoro-n-hexanoic acid [PFHxA], perfluoro octanoic acid [PFOA], and perfluoropentanoic acid [PFPeA]). 4-nonylphenol was considered a surface water COPEC because the screening benchmark for water was exceeded, while the four PFAS were classified as fish tissue and wildlife COPECs due to high persistence and bioaccumulation potential.

6.3 Exposure Analysis

For each COPEC, a creek-wide surface water EPC was calculated for each creek based on the maximum mass discharge of the chemical (based on the 100-year groundwater fate and transport model projections) and a dilution factor (to account for the dilution of groundwater with surface water). Additionally, for the fish tissue and wildlife COPECs, fish tissue EPCs and wildlife dietary doses were calculated. Fish tissue EPCs were derived from the surface water EPCs and surface water-to-biota bioaccumulation factors (BAFs), which estimate chemical uptake into tissue from direct contact with water and dietary intake. Wildlife dietary doses were calculated for belted kingfisher and river otter using the surface water and fish tissue EPCs and species-specific food and water ingestion rates and body weights.

6.4 Effects Characterization

The effects characterization establishes toxicity reference values (TRVs), which are toxicity thresholds below which adverse effects are not expected to occur. TRVs were derived, when possible, for surface water (for 4-nonylphenol) and fish tissue and wildlife dietary doses (for the four PFAS COPECs) using data from the scientific literature. A freshwater TRV for 4-nonylphenol was derived based on U.S. EPA guidelines for developing chronic ambient water quality criteria (AWQC). The AWQC approach uses a species sensitivity distribution that targets a 5th percentile level of sensitivity intended to protect 95% of species in the aquatic community.

Fish tissue and wildlife TRVs were derived from toxicity data found in the scientific literature. Fish tissue TRVs for PFHxA and PFOA are based on no-observed-effect concentrations (NOECs) for zebrafish embryo survival and development. No data were available for PFBS or PFPeA. Bird and mammal dietary dose TRVs for PFBS (birds and mammals), PFHxA (mammals only), and PFOA (birds and mammals) are based on lowest-observed-adverse-effect levels (LOAELs) for survival, growth, and/or reproduction. No data were available for PFPeA.

6.5 Risk Characterization

In the risk characterization, the EPCs from the exposure analysis and the TRVs from the effects characterization were used to calculate hazard quotients (HQs). HQs are used to assess potential for adverse effects. HQs greater than or equal to one indicate that there is potential for adverse effects on EAEs, and HQs less than one indicate that the potential for adverse effects causing risk to EAEs is negligible.

For 4-nonylphenol, HQs were calculated by dividing the surface water EPCs for Woodland and McAllister Creeks by the surface water TRV. For the four PFAS, HQs were based on fish tissue EPCs and wildlife dietary doses divided by their respective TRVs. All HQs were less than one, indicating there are no unacceptable risks associated with these chemicals at these concentrations. In cases where no data were available to derive TRVs, HQs were not calculated.

6.6 Ecological Risk Assessment Findings and Conclusions

Based on their low HQs, the potential for residual chemicals currently present in reclaimed water infiltrated into groundwater to cause risk to EAEs is negligible. Uncertainties associated with each component of the risk assessment—including COPEC selection and quantification, exposure estimation, effects estimation, and risk characterization—were evaluated and did not change the risk conclusion.

7.0 Cost Benefit Analysis (Task 4)

Using the information developed in Tasks 1-3, a cost benefit analysis was conducted to determine the costs and benefits of various levels of treatment for reclaimed water and identify other strategies to address risks related to residual chemicals. This effort involved identifying options for advanced levels of reclaimed water treatment and assessing benefits of such treatment options in terms of reduced levels of risk based on enhanced residual chemical removal from reclaimed water.

7.1 Advanced Treatment Options

The first step of the cost benefit analysis was a review of the broad range of treatment technologies that can be used to reduce residual chemicals concentrations in reclaimed water. Four treatment options were identified for further analysis. These options range from reverse osmosis (sometimes considered the “gold standard” of treatment) to no additional treatment.

- **Reverse Osmosis (RO) + Ultraviolet Light (UV) + Hydrogen Peroxide (H_2O_2)** is a combination of technologies that offers a multi-barrier system for removal of residual chemicals. RO uses pressure to force water through a membrane, leaving behind minerals, salts, and other compounds, including residual chemicals. The process requires high energy use and results in a concentrated brine that is costly and challenging to dispose of. UV and H_2O_2 break down chemicals not removed by RO. This multi-step system is effective at removing most residual chemicals from reclaimed water.
- **Ozone + Biological Activated Carbon (BAC) + Granular Activated Carbon (GAC)** is also a multi-barrier system. Ozone and BAC processes degrade many chemicals and GAC acts as a polishing step to absorb chemicals that remain. It requires proper disposal of spent carbon, which is typically less challenging than RO brine disposal. This system is effective at removing many residual chemicals from reclaimed water.
- **Granular Activated Carbon (GAC)** is a treatment technology that absorbs certain chemicals. GAC could be used as a stand-alone technology initially and be incorporated into a multi-step treatment train if warranted in the future. It is a targeted approach that addresses the two chemicals of interest identified in the HHRA, by removing PFPeA and the broader suite of PFAS chemicals, and the precursor chemicals that contribute to the formation of NDMA.
- **No advanced (i.e., no additional) treatment** is the option that would maintain the current level of treatment. Class A reclaimed water is produced at the MWRWP using membrane bioreactor technology. Microorganisms break down compounds in the water before it is filtered through a membrane system and disinfected with chlorine. Class A reclaimed water meets high water quality standards and is approved by Washington State Departments of Health and Ecology for many uses, including groundwater replenishment. With the Task 3 results indicating the risk of using this quality of water is very low, this remains a viable treatment option.

7.2 Cost Estimates

Cost estimates were prepared for each advanced treatment option, including upfront capital costs and ongoing annual system operation and maintenance (O&M). Costs were developed for two sizes of facilities: 1 and 5 mgd. The present value costs (i.e., in 2022 dollars) over a 20-year lifecycle are presented in Table 7-1.

Table 7-1. Present Value (20-Year) Costs for Advanced Treatment Options

Treatment Option	Present Value ($million)
RO Treatment – 1 mgd	$76.0
RO Treatment – 5 mgd	$218.7
Ozone-BAC-GAC Treatment – 1 mgd	$18.5
Ozone-BAC-GAC Treatment – 5 mgd	$48.3
GAC Treatment – 1 mgd	$5.8
GAC Treatment – 5 mgd	$19.2

7.3 Cost Benefit Analysis Results

The cost benefit analysis results are presented as a quantitative comparison of costs and benefits (in the form of risk reduction) associated with the identified treatment options. In this analysis, the benefit of applying additional levels of treatment to LOTT's reclaimed water can be evaluated as the associated reduction in level of risk. Table 7-2 presents a summary of this information, focused on the use of reclaimed water for groundwater recharge. The No Advanced Treatment option reflects continued generation and use of Class A reclaimed water via LOTT's current treatment systems.

Table 7-2. Risk Reduction Benefit for Treatment Options

Treatment Option	Highest Risk Level [a]	
	PFPeA	NDMA
No Advanced Treatment	1.3	2.9×10^{-6}
GAC	0.065	2.9×10^{-6} (Max; NDMA removal) 2.8×10^{-7} (Min.; NDMA precursor removal)
Ozone-BAC-GAC	0.065 (Max.) 0.013 (Min.)	8.4×10^{-7} (Max.) 1.4×10^{-7} (Min.)
RO-Based	0.0	1.1×10^{-6} (Max.) 5.8×10^{-8} (Min.)

Notes:

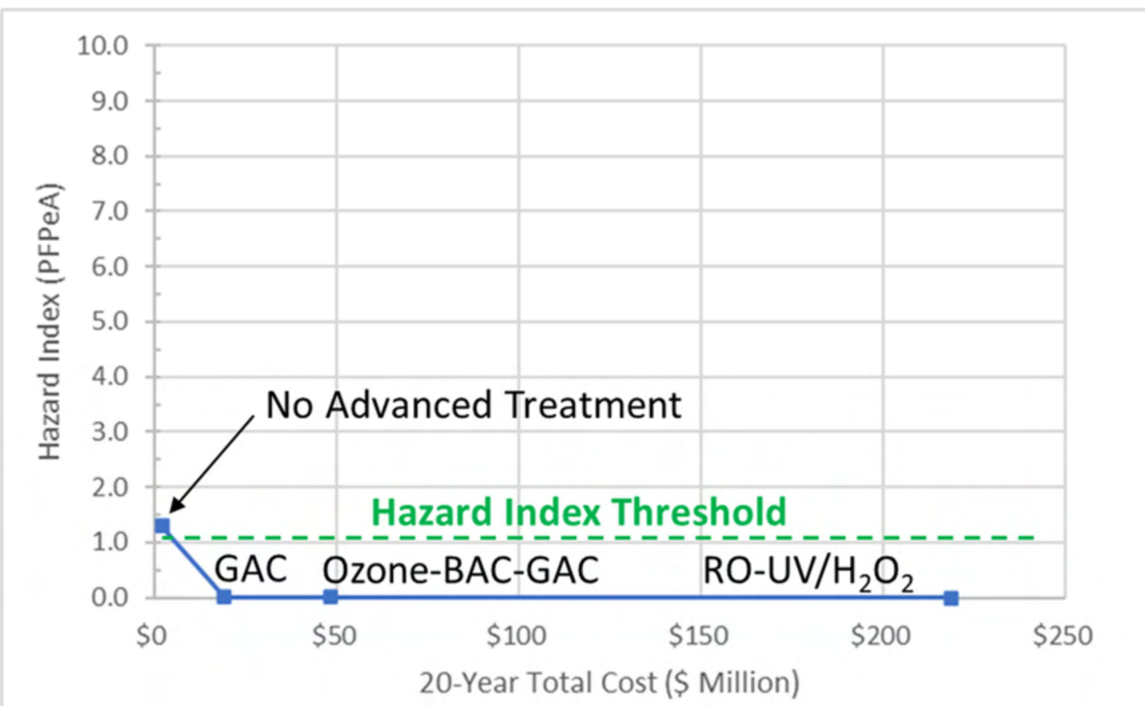
a. As presented in the HHRA, based on the RME child resident scenario. Depicted as a range (maximum and minimum risk) in cases where reviewed treatment efficacy is characterized by a range. Specific notes:

- PFPeA. Non-cancer risk level presented as a Hazard Index (HI). Minimum threshold of concern is HI = 1.
- NDMA. Cancer risk level presented as Lifetime Excess Cancer Risk (LECR). *De minimis* cancer benchmark is 1×10^{6}.

This information is also summarized on Figure 7-1 (for PFPeA)[1] and Figure 7-2 (for NDMA), where the 20-year present value costs for the 5 mgd treatment facility size are plotted against the HHRA results for each treatment option.

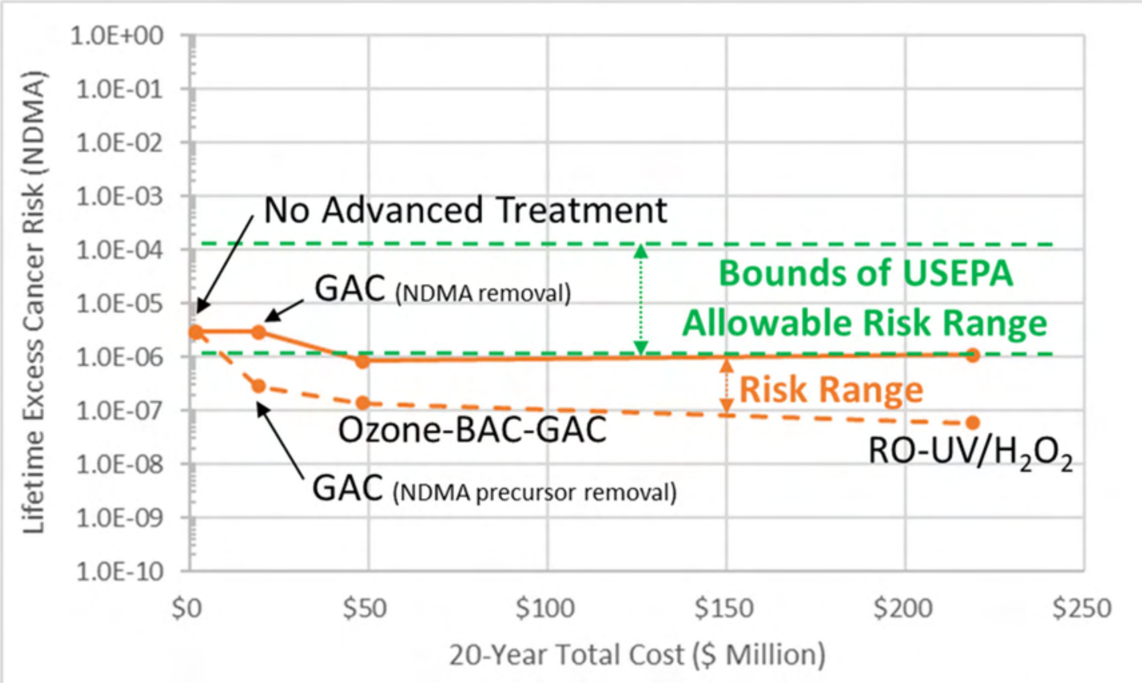
The No Advanced Treatment option may be considered a viable option, given the low level of risk identified in the risk assessments. All options of providing advanced levels of treatment reduce the highest risk levels to below minimum thresholds of concern. While the RO-based treatment train has the potential to result in the greatest risk reduction, it also carries the greatest cost. The GAC and Ozone-BAC-GAC options provide the same risk reduction levels for PFPeA, with the GAC-only option having considerably less cost. The impact of the GAC-only option upon NDMA-related risk is a function of whether NDMA in reclaimed water comes from NDMA that is present in influent wastewater or if it is formed during the disinfection stage of treatment. If it is predominantly the latter, GAC treatment can be effective at removing NDMA precursors, thereby preventing NDMA formation in reclaimed water. In this case, the NDMA-related risk is reduced similar to the Ozone-BAC-GAC treatment option. If NDMA is already present in influent wastewater, no removal by GAC is assumed and the risk level is considered unchanged from the No Advanced Treatment option. Therefore, further characterization of NDMA throughout LOTT's treatment processes is warranted if the GAC-only option is pursued.

Figure 7-1. PFPeA Cost/Risk Comparison



[1] No risk ranges are shown in Figure 7-1. As depicted in Table 7-2, a risk range is only shown for the Ozone-BAC-GAC option in relation to PFPeA removal. The range shown in Table 7-2 is too small to be clearly depicted at the scale presented in Figure 7-1.

Figure 7-2. NDMA Cost/Risk Comparison



7.4 Cost Benefit Analysis Findings and Conclusions

Four treatment options were evaluated to understand the costs and benefits (regarding residual chemical removal efficacy) of implementing various levels of treatment. These options were:

- Reverse Osmosis (RO) + Ultraviolet Light (UV) + Hydrogen Peroxide (H_2O_2)
- Ozone + Biological Activated Carbon (BAC) + Granular Activated Carbon (GAC)
- Granular Activated Carbon (GAC)
- No Additional Treatment (i.e., no advanced treatment employed beyond current levels of treatment)

Twenty-year present value costs, including capital and operational/maintenance costs, were developed for the various options. Costs for a 5 mgd capacity treatment facility range from $0 for the No Advanced Treatment option to $218.7 million for the RO-based treatment train.

These costs were then compared against the amount of risk reduction associated with each option. The No Advanced Treatment option may be considered a viable option, given the low level of risk identified in the risk assessments. All options of providing advanced levels of treatment have the potential to reduce the highest risk levels to below minimum thresholds of concern. While the RO-based treatment train results in the greatest risk reduction, it also carries the greatest cost. The GAC and Ozone-BAC-GAC options provide the same risk reduction levels for PFPeA, with the GAC-only option having considerably less cost. If the GAC-only treatment option is of interest, further characterization of NDMA throughout LOTT's treatment processes is warranted, as its efficacy on reducing NDMA formation potential depends on if NDMA is present in influent wastewater or is created during treatment.

8.0 Summary

This extensive research effort adds to the overall understanding of potential risk as it pertains to use of reclaimed water for groundwater replenishment. It also broadens the information base regarding infiltration projects in temperate climates, as much prior research has been conducted in warm, arid regions of the U.S. Overall, study findings indicate the risk to human and ecological health from residual chemicals in reclaimed water used for infiltration is low. The Study's independent Peer Review Panel indicated:

- The risk assessments were well designed and protective of human and ecological health.
- Under current conditions, the potential risks associated with groundwater recharge are low and the water is safe.

This research effort was a point-in-time study. While it included modeling conditions 100 years into the future, analyses were based on data collected during the study period on or near the Hawks Prairie site. For these reasons, Study conclusions should be viewed as applicable to current conditions and specific to the Hawks Prairie property. Many factors can, and likely will, affect conditions in the future, including:

- Consumer products are under constant development and industrial products and practices are adjusted over time as well. As a result, the types and number of chemicals that make their way into the wastewater system will change in the future. New or different chemicals may enter the system; others may be phased out. As an example, Washington State recently passed legislation that sets an ambitious timeline for phasing out use of PFAS chemicals in consumer products.
- Research into potential health effects of residual chemicals will continue over time, and this may change the understanding of potential risk. Following the completion of the risk assessment associated with this Study, the U.S. EPA released new lifetime health advisory levels for four PFAS compounds in drinking water. While they are not considered legal federal standards and are subject to change as new information becomes available, they will likely lead to the development of new, enforceable Maximum Contaminant Levels (MCLs) for these compounds.
- Regulations are expected to change. State and federal regulations affecting PFAS chemicals, such as that mentioned above, are anticipated soon.
- Community expectations may lead to reconsideration of next steps, potentially including identification of different needs for the use of reclaimed water.
- If additional recharge sites are developed in the future, site-specific conditions and the latest research about residual chemicals will need to be considered.

The study effort addressed many questions regarding residual chemicals in reclaimed water, but some questions remain unanswered. Although the study was designed using multiple layers of health-protective assumptions to err on the side of caution, there are some uncertainties about findings. Analyses focused on a subset of residual chemicals considered representative and indicative of the many chemicals currently in use and likely to enter the wastewater system, but it is possible there are chemicals in the system not yet identified or understood. Potential cumulative effects from combinations of various chemicals are not well understood. Information about other sources of residual chemicals, such as septic systems and stormwater, is limited.

8.1 Steps Beyond the Study

Study findings did not point to an immediate need to change current practices or level of treatment. However, treatment technologies capable of further reducing residual chemicals in reclaimed water were identified. This information can serve as a foundation for further consideration of treatment levels in response to new information and regulations.

In the near-term, some level of continued monitoring is recommended to fill data gaps and refine understanding of residual chemicals of interest.

- Continued monitoring of NDMA, NDMA precursors, PFPeA, and the broader suite of PFAS chemicals is recommended. This would provide a more robust data set to resolve uncertainty regarding NDMA, which was not detected consistently in reclaimed water or groundwater samples. It is also unclear if NDMA is entering the wastewater influent or is formed from precursors during the treatment process. Understanding the source of NDMA would in turn inform which treatment technologies could effectively reduce the chemical in reclaimed water, if it is determined that advanced treatment is necessary. Data about PFAS chemicals could provide a head start for adapting to anticipated new regulations.
- Sampling efforts to pinpoint sources of these chemicals is also recommended. This information could shed light on effective source control efforts to reduce chemical inputs into the wastewater system. Comparison of residential versus commercial/industrial effluent and sampling of groundwater, surface water, and septic effluent in areas influenced by reclaimed water infiltration and areas where reclaimed water is not used for that purpose could refine understanding of potential sources.

Conditions are bound to change. It will be important for LOTT to keep abreast of industry research, changing regulations, and the chemical landscape to gather new information as it becomes available. Revisiting the Study may be necessary in the future to reassess potential risk and study conclusions, in light of changing conditions and community expectations. Other specific longer-term actions that LOTT may consider to address risks related to residual chemicals are:

- Continued outreach and education for the public and policy makers, aimed at: 1) enhancing awareness of the costs and benefits of various water management approaches; 2) increasing the understanding of risk levels and risk management; and 3) reducing inputs of residual chemicals into the wastewater system.
- Targeted pretreatment of specific sources that contribute a higher proportion of residual chemicals to the wastewater system. At this time, no such sources are known, but if further analysis identifies them, localized advanced treatment of such waste streams could be more cost-effective than applying advanced treatment to the full quantity of reclaimed water produced at a LOTT facility.
- Support of broader industry efforts to regulate the sources of residual chemicals to reduce their inputs into the wastewater system.

- Modifying plans for future groundwater recharge. For example, LOTT could reduce or cease the use of reclaimed water for groundwater recharge purposes. Other uses, such as irrigation, could then be increased. However, it must be recognized that it is highly unlikely other uses of reclaimed water could utilize the full volume of water currently used for groundwater recharge, especially during winter months. The impacts of redirecting this water to other points of final disposition (i.e., to marine water discharge) would need to be fully considered, including its relation to evolving Puget Sound water quality management objectives and associated treated wastewater discharge constraints.

8.2 Acknowledgements

LOTT and the Study team are grateful to the many staff members, consultants, technical experts, elected officials, and community members who contributed their insights and knowledge to this major research effort. Over the course of the study, membership in the various advisory committees has changed; participants have come and gone, but many have devoted their time and expertise to the Study for the full 10-year time span. Thank you to everyone who played a role in this important effort to ensure our wastewater management practices are appropriate and responsible.

Appendix A Study Document Inventory

LOTT Reclaimed Water Infiltration Study

Study Document Inventory

1. **Background Materials (2013)**
    a. Case Study Summary. Phase 1 (Technical Data Review). Technical Memorandum. HDR. July 16, 2013. *Case studies for six different projects across the country that involve infiltrating reclaimed water into groundwater*.
    b. “State of the Science”. Phase 1 (Technical Data Review). Technical Memorandum. HDR. May 31, 2013. *Summary of the State of the Science, based on a review of existing scientific research regarding study topics*.
2. **Early Public Involvement (2013-2014)**
    a. Public Opinion Research – Structured Interviews: Summary Report. Katz. May 8, 2013. *Summary of in-depth interviews with 53 stakeholders in early 2013 to gauge awareness and perceptions about water, wastewater, reclaimed water, groundwater recharge, and related issues*.
    b. Focus Group Summary Report. The Athena Group. October 7, 2013. *Summary of three citizen focus groups conducted in the fall of 2013 to learn how best to communicate about the study and the technical topics involved*.
    c. Public Involvement Plan. Katz. June 20, 2013. *A plan outlining the approach to public involvement, which will be adjusted as the study progresses to effectively engage the public, gather input and feedback, and encourage community dialogue*.
    d. Telephone Survey of Residents: Report on Findings. EMC Research. May 2013. *Summary of a phone survey conducted in early 2013 of 400 residents to gain an understanding of public awareness, knowledge, interest, and perceptions regarding water, wastewater, reclaimed water, groundwater recharge, and related issues*.
3. **Study Planning and Scoping (2014)**
    a. Phase III (Study Implementation) Scope of Services. HDR. July 31, 2014. *Description of work associated with the implementation phase of the study*.
    b. Independent Advisory Panel – Final Report of the February 18-19, 2014 Meeting (Panel Report 1). NWRI. August 11, 2014. *Final report from the Peer Review Panel's review of the study design and draft Phase 3 scope of work*.
    c. Study Team Response to NWRI August 11, 2014 Final Report. *Responses to the Peer Review Panel Report 1, which includes comments and recommendations made by Peer Review Panel regarding study design and draft scope*.
4. **Task 1 (Water Quality Characterization) Technical Documents (2014-2017)**
    a. Startup Water Quality Monitoring Report (Hawks Prairie Reclaimed Water Ponds and Recharge Basins). HDR. November 20, 2014. *Results of water quality sampling for residual chemicals and other parameters in reclaimed water and groundwater at LOTT’s Hawks Prairie property, to characterize initial conditions during startup of the recharge basins after a period of non-use*.

b. Work Plan: Groundwater Quality Characterization (Task 1.1). HDR. February 6, 2015. *Description of the approach and methods for groundwater quality monitoring*.

c. Work Plan: Surface Water Quality Characterization (Task 1.2). HDR. July 6, 2015. *Description of the approach and methods for surface water quality monitoring*.

d. Work Plan: Wastewater and Reclaimed Water Quality Characterization (Task 1.3). HDR. January 27, 2015. *Description of the approach and methods for wastewater and reclaimed water quality monitoring*.

e. Groundwater Quality Characterization (Task 1.1). Technical Memorandum. HDR. February 7, 2017. *Results of water quality sampling for residual chemicals and other parameters in groundwater in the two study areas – the Hawks Prairie Study Area, an area influenced by reclaimed water infiltration, and the Tumwater Study Area, an area not influenced by reclaimed water infiltration*.

f. Surface Water Quality Characterization (Task 1.2). Technical Memorandum. HDR. February 7, 2017. *Results of water quality sampling for residual chemicals and other parameters in surface water in the Hawks Prairie and Tumwater study areas*.

g. Wastewater and Reclaimed Water Quality Characterization (Task 1.3). Technical Memorandum. HDR. February 7, 2017. *Results of water quality sampling for residual chemicals and other parameters in wastewater and reclaimed water at the Budd Inlet Treatment Plant, the Budd Inlet Reclaimed Water Plant, and the Martin Way Reclaimed Water Plant*.

5. Task 2 (Treatment Effectiveness Evaluation) Technical Documents (2018-2021)

a. Work Plan: On-Site Wells and Lysimeter Installation (Task 2.1.1.A) and Off-Site Monitoring Wells (Task 2.1.2.C) – Hawks Prairie Area. HDR. April 25, 2017. *Description of the approach and methods for installation of wells and lysimeters to be used for hydrogeologic characterization*.

b. Hydrogeologic Characterization Report (On-Site Wells and Lysimeter Installation and Off-Site Monitoring Wells – Hawks Prairie Area). HDR. March 26, 2018. *Description of the hydrogeologic field investigations and results*.

c. Work Plan: Tracer Testing and Water Quality Monitoring of Treatment Effectiveness. HDR. January 5, 2018. *Description of the approach and methods for the tracer testing and water quality monitoring of treatment effectiveness.*

d. Independent Advisory Panel – Final Report of the November 17, 2017 Meeting (Panel Report 2). NWRI. January 12, 2018. *Final report from the Peer Review Panel's review of the Hydrogeologic Characterization Report and the Tracer Testing and Water Quality Monitoring of Treatment Effectiveness Work Plan*.

e. Study Team Response to NWRI January 12, 2018 Final Report. *Responses to comments and recommendations made by the Peer Review Panel regarding the Hydrogeologic Characterization Report and the Tracer Testing and Water Quality Monitoring of Treatment Effectiveness Work Plan*.

f. Tracer Test and Water Quality Monitoring (Task 2.1.3). Report. HDR. October 30, 2019. *Results from the monitoring of groundwater wells for tracer and water quality parameters*.

g. Work Plan: Groundwater Modeling Predictive Simulations (Task 2.1.4 continued) and Residual Chemical Fate and Transport (Task 2.1.5). HDR. February 20, 2020. *The work plan for how the hydrogeologic model will be used to predict flow velocity, flow path, percent reclaimed water, and residual chemical concentration at potential points of exposure. These concentrations will be used in the human health and ecological risk assessments*.

h. Steady-State Groundwater Model Development and Calibration (Task 2.1.4). Technical Memorandum. HDR. October 22, 2021. *A technical memorandum on the development, calibration approach, and description of the groundwater model*.

i. Residual Chemical Fate and Transport Analysis (Task 2.1.5). Technical Memorandum. HDR. October 14, 2021. *Results from the hydrogeologic model predicting estimated residual chemical concentrations to downstream wells and creeks at current and future reclaimed water infiltration rates*.

6. Task 3 (Risk Assessment) Technical Documents (2020-2022)

a. Screening-Level Evaluation for the Human Health Risk Assessment. Intertox. May 29, 2020. *Results from a human health screening evaluation of chemicals found in reclaimed water, to be used to inform the subsequent Human Health Risk Assessment*.

b. Screening-Level Evaluation for the Ecological Risk Assessment (Problem Formulation Step of the Assessment Process. Windward Environmental. May 28, 2020. *Results from an ecological screening evaluation of chemicals found in reclaimed water, to be used to inform the subsequent Ecological Risk Assessment*.

c. Final Human Health Risk Assessment Scope of Work. Intertox. January 26, 2021. *Work plan that describes the steps that will be taken in the human health risk assessment*.

d. Final Ecological Risk Assessment Scope of Work. Windward Environmental. February 20, 2020. *Work plan that describes the steps that will be taken in the ecological risk assessment*.

e. Human Health Risk Assessment. Intertox. June 20, 2022. *Human health risk assessment for infiltration of reclaimed water into groundwater*.

f. Ecological Risk Assessment. Windward Environmental. June 20, 2022. *Ecological risk assessment for infiltration of reclaimed water into groundwater*.

7. Task 4 (Cost Benefit Analysis) Technical Documents (2022)

a. Cost-Benefit Analysis (Task 4). Technical Memorandum. HDR. June 22, 2022. *Summary of the methodology and results of a cost benefit analysis of reclaimed water treatment options and identification of other potential actions to address residual chemicals in reclaimed water*.

8. Tasks 2-4 Review Documents (2019-2022)

a. Study Team Response to NWRI October 23, 2019 Final Report (Panel Report 3). *Responses to comments and recommendations from the Peer Review Panel regarding the Tracer Test and Water Quality Monitoring Report, and the screening evaluations for the human health and ecological risk assessments*.

b. NWRI Subcommittee Comments on the Human Risk Assessment and Ecological Risk Assessment Scopes of Work. Memorandum. NWRI. May 18, 2020. *An evaluation of the work plans for human and ecological health risk assessment by a subcommittee of the Peer Review Panel*.

c. Study Team Response to NWRI September 3, 2021 Final Report (Panel Report 4). *Responses to comments and recommendations from the Peer Review Panel regarding the drafts of the Residual Chemical Fate and Transport Analysis Technical Memorandum, Human Health Risk Assessment, and Ecological Risk Assessment*.

d. Study Team Response to NWRI February 16, 2022 Final Report (Panel Report 5). *Responses to comments and recommendations from the Peer Review Panel regarding the draft of the Human Health Risk Assessment*.

e. Study Team Response to NWRI April 26, 2022 Memorandum. *Responses to additional comments and recommendations from the Peer Review Panel regarding the draft of the Human Health Risk Assessment*.

f. Study Team Response to NWRI June 15, 2022 Final Report (Panel Report 6). *Responses to comments and recommendations from the Peer Review Panel regarding the draft final of the Human Health Risk Assessment and the preliminary cost-benefit analysis*.

g. Study Team Response to NWRI July 6, 2022 Final Report (Panel Report 7). *Responses to comments and recommendations from the Peer Review Panel regarding the draft final cost-benefit analysis and preliminary Project Summary report*.

9. Project Summary Report (2022)

a. Project Summary Report. HDR. (pending). *Summary of the technical elements of the Study*.

10. Public Engagement (2022)

a. Public Communications Plan (pending). *Summary of the public outreach and involvement activities implemented over the course of the study effort.*

b. Community Advisory Group Phase 1, 2, and 3 Final Reports (pending). *Compilations of meeting minutes for each phase of the study.*