# Chapter 6:

# CRITICAL AQUIFER RECHARGE AREAS

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## 6.1 INTRODUCTION

"Critical Aquifer Recharge Areas" (CARAs) are one element of the "critical areas" for which Washington's Growth Management Act (RCW 36.70)(GMA) requires local governments to develop policies or regulations to protect their functions and values. Critical Aquifer Recharge Areas are the geographic areas that have a "critical recharging effect on aquifers used for potable water" (RCW 36.70A.030(5)). King County is reviewing and updating its existing ordinances and policies for the protection of CARAs, which were first enacted in 1994. This chapter presents the "Best Available Science" on protecting critical aquifer recharge areas.

## 6.2 REVIEW OF LITERATURE

This chapter presents the best available science as it pertains to the CARA regulation by:

1. Defining aquifer recharge areas;
2. Describing the best available method for prioritizing aquifer recharge areas;
3. Identifying and assessing the land-use activities that can adversely affect groundwater; and
4. Discussing the existing concerns or issues specific to King County.

### 6.2.1 Definition of Aquifer Recharge Areas

Before defining Critical Aquifer Recharge Areas, it is helpful to first define the more general term of aquifer recharge area. Every location within a drainage basin can be designated as either a groundwater recharge or discharge area, and this designation depends upon the direction of groundwater flow within the aquifer. In recharge areas, the flow of groundwater in the saturated zone is directed away from the water table surface while in discharge areas the flow of groundwater is directed toward the water table surface. Near the ground surface of a recharge area flow is directed downward, while a discharge area will have an upward flow near the surface (Freeze and Cherry, 1979). Recharge areas serve to replenish the groundwater supplies, but also allow for introduction of contaminants into the upper most unconfined aquifer.

Typically, around 70 to 90 percent of a drainage basin will be a groundwater recharge area (Dingman, 2002), which if similar distributions hold for King County the majority of the land surface is a groundwater recharge area. This identification of recharge and discharge areas is important for land use planning purposes.

There are five general methods for mapping recharge and discharge areas (Freeze and Cherry, 1979):

- topography (simplest)

- water levels (piezometric patterns) (most direct)
- hydrochemical trends
- environmental isotopes (e.g., tritium, carbon-14)
- soil and land surface features (vegetation, soil types)

The simplest method in identifying recharge and discharge areas is through topography – higher elevations tend to be recharge areas and lower elevations, discharge. This approach, however, fails to account for localized effects caused by streams, lakes, and groundwater extraction wells. The most direct and perhaps most reliable method for identifying recharge and discharge areas is to use maps of water levels or "piezometric surfaces." Collecting measurements in water wells can identify these surfaces, which include the effects of groundwater sinks and sources. Mapping the recharge/discharge areas using this method would be automatic if there was a well at every point in question. The major limitation in using this approach is the large number of wells needed to produce useful results (Freeze and Cherry, 1979).

The remaining three methods (hydrochemical trends, environmental isotopes, and soil and land surface features), typically play "supporting roles" for identifying recharge and discharge areas. This type of information is typically not sufficient to uniquely distinguish between recharge and discharge areas, but rather it can be used in conjunction with water level data to help confirm the different categories.

Recharge areas can be further categorized into several sub-groups based on the function of the water once it enters the aquifer. The main sub-groups that are relevant for the groundwaters of King County include the following:

- **Wellhead protection areas (WHPA):** the area delineated as providing recharge to a drinking water well (See Section 2.3 – Special Areas/Issues of Concern Specific to King County for discussion on the difficulties in accurate delineation). In Washington, WHPAs are mapped for the largest public water systems using a groundwater source where state drinking water regulations (RCW 43.20 and RCW 70.119A) require the system to develop a protection plan.
- **Sole source aquifer areas:** recharge areas that contribute water to aquifers that have been certified by the U.S. EPA as "sole-source" aquifers because they contribute at least 50 percent of the supply to a public water system, and for which federal agencies have to exercise special precautions. The Sole Source Aquifer (SSA) Protection Program is authorized by Section 1424(e) of the Safe Drinking Water Act of 1974 (Public Law 93-523, 42 U.S.C. 300 et seq.). See: "Sole Source Aquifer Designation Petitioner Guidance" (EPA, 1995).

### 6.2.2 Prioritizing Aquifer Recharge Areas (Which are Most Critical?)

Critical Aquifer Recharge Areas (CARAs) in Washington are defined as the geographic areas "where an aquifer that is a source of drinking water is vulnerable to contamination that would affect the potability of the water" (WAC 365-190-030). All groundwater is potentially vulnerable to contamination. However, existing data on groundwater contamination shows that problems vary spatially and not all regions are equally vulnerable (Merchant, 1994). Effective protection strategies for groundwater, therefore, need to be targeted at the most critical areas.

Identifying the geographic areas that are most critical for protecting a region's groundwater resources involves two major tasks. The first task is to identify and map areas that are most **susceptible** to groundwater contamination. The susceptibility depends on the aquifer properties (hydraulic conductivity, porosity, hydraulic gradients) and the associated sources of water and stresses for the system (recharge, interactions with surface water, travel through the unsaturated zone, and well discharge) (USGS, 2002). The second task for prioritizing critical aquifer recharge areas is to identify and map the **resource value** or **beneficial use** where the severity of the impact to the groundwater resources would be the greatest. The final product combines the susceptibility maps with resource value maps into a map of the most critical or **high-risk areas** that have high values for both aquifer susceptibility and beneficial use. Once these aquifer recharge areas are prioritized, the potential or existing contaminant loads can be overlaid to assist in groundwater protection of water quality (This type of map is often called a contaminant hazard map). These areas can also be used to evaluate potential impacts to the water quantity.

The two tasks summarized above have evolved in the resource management and land-use planning literature over the last 25 years. The first task involved developing techniques for quantifying aquifer susceptibility. The most widely used method for quantifying susceptibility is the DRASTIC index (Aller et al., 1987; Merchant, 1994). This index uses the weighted average of 7 values corresponding to 7 hydrogeologic parameters. These parameters and the weights assigned to them are summarized in the following table:

**Table 1.0**

| | **Weight** |
|---|---|
| **D**epth to the water table | 5 |
| Net **R**echarge | 4 |
| **A**quifer material | 3 |
| **S**oil type | 2 |
| **T**opography | 1 |
| **I**mpact of the vadose zone | 5 |
| Hydraulic **C**onductivity | 3 |

Each parameter used in the DRASTIC index has a predetermined, fixed, relative weight that reflects its relative importance to susceptibility. The most significant factors have weights of 5; the least significant a weight of 1.

The DRASTIC susceptibility index is calculated by first assigning a value between 1 and 10 for each parameter, depending upon local conditions. High values correspond to high susceptibility. The attributed values are obtained from tables, which give the correspondence between local hydrogeologic characteristics and the parameter value. Next, the local index of susceptibility is computed by multiplying the value attributed to each parameter by its relative weight, and adding up all seven products. The minimum value of the DRASTIC index is therefore 23 and the maximum value is 226. Such extreme values are very rare, the most common values being within the range 50 to 200.

The DRASTIC approach for quantifying groundwater susceptibility has been widely used both in North America (Navulur and Engel, 1998; Fagnan et al., 1998; Ducci, 1999; Stark et al., 1999; Fritch et al., 2000) and around the world, including China, Italy, Portugal, South Africa, and

Algeria (Menani, 2001; Napolitano et al., 1996; Dai, 2001; Shahid, 2000; Lobo-Ferreira et al., 1997; Lynch et al., 1994).

Subsets of the DRASTIC parameters and variations on these parameters have also been extensively used. These include the GOD index (Foster et al., 2002) and the AVI index (Canada, Van Stempvoort et al., 1992). England, Wales, Ireland, New Zealand, Australia all use subsets (Bekesi and McConcie, 2002; Otto et al., 2002; Burgess and Fletcher, 1998; Ireland DOE, 2001). King County's current susceptibility mapping uses parameters "D," "S," and "I" of the DRASTIC method.

The second task, and most recent advancement, in prioritizing aquifer recharge areas is to combine susceptibility maps with measures that relate to severity or impact of the contamination. A common approach is to designate groundwater supply protection areas as areas with high beneficial use where the severity of contamination would be the greatest (Foster et al., 2002). These groundwater supply protection areas, which are termed wellhead protection area (WHPA) and sole source aquifer (SSA) within the U.S., have been used for years. The WHPA acknowledges the high resource value of drinking water by delineating the contributing recharge area to federally regulated public water systems (all Group A wells in Washington). The SSA expands on the WHPA by mapping the aquifer and designating it as a SSA if certain requirements are met (U.S. EPA, 1995). The overlap of supply protection areas on highly susceptible areas will designate the most critical aquifer recharge areas.

The delineation of WHPAs can be done using a variety of methods, ranging from the simplistic to the elaborate. Several authors, U.S. EPA (1987, updated 1993); Swanson (1992); Cleary and Cleary (1991), have outlined the most commonly used methods and discussed the advantages, disadvantages and relative costs for each method. Table 1.1 summarizes these discussions. A general problem with all wellhead boundary determinations is that the boundaries are time and stress dependant (i.e., they change in response to changing recharge rates, changing patterns, and the influence of other pumping wells).

This latest advance in combining susceptibility maps with measures that relate the value of the resource has been used in numerous cities and countries, (Ducci, 1999; Foster et al., 2002) and is the best available method for prioritizing critical aquifer recharge areas. This approach is firmly rooted in the literature and has become the framework for programs being mandated and recommended by both the U.S. Environmental Protection Agency (EPA) and the World Bank (U.S. EPA, 1997; Foster et al., 2002).

**Table 1.1 Commonly Used Methods for Wellhead Protection Areas Delineation**

(Sources: U.S. EPA,1987, updated 1993; Swanson,1992; Cleary and Cleary, 1991)

| Delineation Method | Description of Wellhead Boundary | Advantages | Disadvantages | Relative Cost/ Comments | Estimated Hours/ Location |
|---|---|---|---|---|---|
| Arbitrary Fixed Radii | Circular boundary at an arbitrarily selected distance criterion threshold value | Easy, inexpensive, quick and requires little technical expertise. | Heterogeneous and non-isotropic conditions make selection of radius difficult, May tend to over- or under-protect well recharge areas. | Low / Large number of wells can be completed in a short amount of time. | ~ 1 |
| Calculated Fixed Radii | Circular boundary designated whose radius is determined by a specific time of travel threshold | Easy, inexpensive, relatively quick, and provides increased accuracy over arbitrary fixed radii method | Heterogeneous and non-isotropic conditions cause inaccuracies in radius calculation | Low / More expensive than arbitrary fixed radius method because of data requirements | ~3-5 |
| Simplified Variable Shapes | Standardized shape designated based on hydrogeologic and pumping conditions found at wellhead | Implementation of shape designation is quick and inexpensive after standard shapes have been developed. | Initial development of standardized shapes is moderately expensive and requires significant data collection | Low / Initial development costs very high | ~2-5 (initial development is >200 hours) |
| Analytical Methods | Boundary represents the zone of contribution as calculated using an analytical method, such as uniform flow equations | Very accurate if data are available and region lacks hydrogeologic complexities | Results not as accurate as numerical flow/transport models. | Medium / Depends on availability of data | ~2-20 |
| Hydrogeologic Mapping | Boundary based on flow boundaries mapped using geologic, geophysical and/or dye tracer data | Works well in settings with near-surface flow boundaries and highly anisotropic aquifers | Requires high level of expertise and significant data collection, Doesn't work well in large or deep aquifers. | Medium – High / Depends on availability of data | ~4-20 |
| Flow/Transport Models | Shape/size found using particle tracking within a groundwater flow model | High potential for accurate boundary, incorporates hydrologic boundaries | Requires high level of expertise and significant data collection | High Depends on complexity of region | ~10-100 |

There are limitations to using this prioritization methodology in water quality and quantity assessments. The most noteworthy are listed below.

- Aquifer susceptibility maps represent a major simplification of naturally complex geologic and hydrogeologic processes making them appropriate only for guiding groundwater protection policy. Even though low, medium and high susceptibility areas are interconnected, a region of low susceptibility will not allow for contaminants to readily access either the saturated zone or areas of medium or high susceptibility. In the unsaturated zone, the dominant direction of flow will be vertical as gravity draws the water downward. In a low susceptibility area, travel through the unsaturated zone will be impeded in both the horizontal and vertical directions. Additionally, the contaminants may be partially or completely attenuated as the contaminants migrate through the unsaturated zone toward the water table.
- The susceptibility maps can overstate the risk in some cases. For instance, areas with a shallow water table may not have a high contamination potential if they fall within a discharge area.
- This methodology is only appropriate for measuring the susceptibility of contamination for the shallowest aquifer. It does not acknowledge the effect of confining units in the subsurface and their ability to protect deeper aquifers.
- This methodology assumes a universal contaminant, and in any given situation susceptibility may vary depending on the type, properties and attenuation potential of a particular pollutant (Foster and Hirata, 1998).
- This methodology was specifically developed, and is best suited, for water quality evaluations that project existing or potential contaminant loads on the highest risk areas to create contaminant hazard maps. It can be useful in designating areas that contribute a large amount of recharge to an aquifer, however, low susceptibility areas can potentially contribute significant quantities of recharge to an aquifer.

The next section will focus on both the contaminant sources/activities and their potential impacts as they relate to this CARA prioritization.

## 6.2.3 Identification and Assessment of Threatening Land-Use Activities

Many land-use activities can potentially affect the quality or quantity of groundwater recharge. If these activities occur above aquifer recharge areas critical to groundwater quality and quantity, it is prudent to implement groundwater protection measures to protect the groundwater resources of the County.

### Water Quality

The protection of groundwater quality requires both the identification and characterization of the different sources of groundwater contamination. Potential land-use activities that store, use, or produce known contaminants of concern (constituents found to be a risk to human health) and have a sufficient likelihood of releasing such contaminants to the environment at detrimental levels are considered threats. The concentration thresholds of these constituents are prescribed by the U.S. EPA and referred to as the Maximum Contaminant Levels (MCLs).

## Contaminant Source Identification

The U.S. EPA has developed a list, shown in Table 1.2, of possible contaminant sources categorized into four major land-use categories: Industrial/Commercial, Agricultural, Municipal/Residential and Miscellaneous. This list is intended to be a baseline inventory list.

Based upon literature review, historical data on activity related releases of contaminants, existing planning documents (e.g., Groundwater Management Plans), federal, state, and local regulatory control, and model CARA provisions from Washington State agencies (OCD, 2002b; WA State Dept. of Ecology, 2000a), the following activities were selected for additional protection measures within King County:

**Industrial/Commercial Land Uses**

- Underground Storage Tanks
- Above Ground Storage Tanks
- Mining (Metals and Sand and Gravel)
- Wood Preserving/Treatment
- Wrecking Yards
- Processing, Storage and Disposal of Radioactive Waste
- Pipelines (Hazardous Liquid Transmission)
- Hydrocarbon Extraction

**Municipal/Residential Land Uses**

- Landfills (Hazardous or dangerous waste, municipal solid waste, special waste)
- Addition of Impervious Surface/Storm Water Runoff
- Golf Courses
- On-site Sewage (Septic) Systems
- Cemeteries

**Miscellaneous Land Uses**

- Abandoned Wells

## Characteristics of Contaminant Sources/Activities

Each of the contaminant sources/activities being considered for further regulation within King County will be characterized using the list below:

1. Description of the source/activity (including 1987 Standard Industrial Classification (SIC) code if applicable);
2. List of contaminants commonly associated with that sources/activity;
3. Common causes of contamination;

**Table 1.2 Potential Sources of Contamination Categorized by Land Use (U.S. EPA, 2003)**

**Commercial / Industrial**

Above-ground storage tanks
Automobile, Body Shops/Repair Shops
Boat Repair/Refinishing/Marinas
Cement/Concrete Plants
Chemical/Petroleum Processing
Construction/Demolition
Dry Cleaners/Dry Cleaning
Dry Goods Manufacturing
Electrical/Electronic Manufacturing
Fleet/Trucking/ Bus Terminals
Food Processing
Funeral Services/Taxidermy
Furniture Repair/Manufacturing
Gas Stations
Hardware/Lumber/Parts Stores
Historic Waste Dumps/Landfills
Home Manufacturing
Hydrocarbon Extraction
Industrial Waste Disposal Wells
Junk/Scrap/Salvage Yards
Machine Shops
Medical/Vet Offices
Metal Plating/Finishing/Fabricating
Military Installations
Mines/Gravel Pits
Office Building/Complex
Pipelines (Hazardous Liquid Transmission)
Photo Processing/Printing
Synthetic / Plastics Production
RV/Mini Storage
Railroad Yards/Maintenance/Fueling Areas
Research Laboratories
Retail Operations
Underground Storage Tanks
Wood Preserving/Treating
Wood/Pulp/Paper Processing

**Agricultural/Rural**

Auction Lots/Boarding Stables
Animal Feeding Operations/ Confined Animal Feeding Operations
Bird Rookeries/Wildlife feeding /migration zones
Crops - Irrigated + Non-irrigated
Dairy operations
Drainage Wells
Lagoons and Liquid Waste Disposal – Agricultural
Managed Forests/Grass Lands
Pesticide/Fertilizer Storage Facilities
Residential Wastewater lagoons
Rural Homesteads

**Residential / Municipal**

Airports (Maintenance/Fueling Areas)
Apartments and Condominiums
Camp Grounds/RV Parks
Cemeteries
Cesspools - Large Capacity
Drinking Water Treatment Facilities
Gas Pipelines
Golf Courses
New Development(Addition of impervious surfacing)
Landfills/Dumps
Public Buildings
On-site Sewage (Septic) Systems
Sewer Lines
Storm water infiltration basins, Injection into wells (UIC Class V) runoff zones
Transportation Corridors
Urban Parks
Utility Stations
Waste Transfer/Recycling
Wastewater Treatment Facilities/Discharge locations (incl. land disposal and underground injection of sludge)

**Miscellaneous**

Abandoned drinking water wells (conduits for contamination)
Naturally Occurring
Underground Injection Control (UIC) Wells
- CLASS I – deep injection of hazardous and non-hazardous wastes into aquifers separated from underground sources of drinking water (banned in Washington)
- CLASS II – deep injection wells of fluids associated with oil/gas production
- CLASS III - re-injection of water/steam into mineral formations for mineral extraction (banned in Washington)
- CLASS IV - inject hazardous or radioactive waste into or above underground sources of drinking water (banned in US).
- Class V - shallow injection wells

4. Examples of contamination history (specific to Washington State, if possible);
5. Regulatory control in place to address the historical instances of contamination; and
6. Remaining concerns with effectiveness of regulatory control.

Table 1.3 lists the sources/activities, along with a list of the associated contaminants and the common causes of contamination. The text that follows gives a brief narrative outlining the remaining concerns with each activity/source. The current risk is related to the degree and effectiveness of the regulatory control. The status of regulatory control at the time of contamination needs to be considered when evaluating past instances of contamination. Reliance on old data will generally overstate current risks.

### *Underground and Above Ground Storage Tanks*

An underground storage tank (UST) system is a tank and any underground piping connected to the tank that has at least 10 percent of its combined volume underground. USTs, which are generally associated with industrial/commercial land uses, can be found at filling stations, airports, hospitals, automotive repair shops, military bases, industrial plants, residential areas and other facilities.

Historically, USTs have not had a good track record, with over 35 percent of UST systems nationwide showing leak rates over 1.2 gallons/day (Young and Golding, 2002). In an effort to prevent future contamination from USTs, the U.S. EPA mandated underground storage tanks that contain hazardous substances, including fuels, be removed by December 22, 1998 or have spill, overfill, and corrosion protection upgrades (40 CFR 280) (Young and Golding, 2002).

Since the upgrade has taken place, the California State Water Resources Control Board has initiated a series of field-testing studies to quantify the probability and environmental significance of methyl tertiary butyl ester (MTBE) releases from USTs meeting the newest 1998 upgrade requirements. The study found that the newest systems were effective in preventing liquid phase releases of petroleum products (Young and Golding, 2002). This study, however, did note that a remaining concern with USTs is the vapor phase releases of MTBE. MTBE is a component of gasoline that is difficult to biodegrade, readily dissolves in water, and can move rapidly through soil and groundwater (WA State Dept. of Ecology, 2000b). A total of 60 percent of the monitored systems showed vapor phase releases of the injected tracers (Young and Golding, 2002). These vapor phase releases are still an outstanding issue related to USTs and need to be evaluated for their impact to groundwater quality to decide how to best address them.

Another concern regarding USTs is that regulations focus on monitoring and post-leak detection rather than prevention of leaks (Redmond, 1999). And, certain classes of tanks, most notably home heating oil tanks, are exempt from federal and state regulations, providing no assurance they will be safe.

Above ground storage tanks (ASTs) usually store products similar to UST. Past instances of contamination from ASTs include releases from corrosion holes, failures of the piping systems, spills and overfills, and equipment and human operational failure. Groundwater contamination from ASTs can be prevented by routine monitoring, proper design to prevent corrosion, and quick cleanups of minor spills (U.S. EPA, 2001a). Washington has legislation in place to prevent contamination from ASTs (see Table 1.0). The main weakness in these regulations is they don't apply to ASTs with a storage capacity less than 10,000 gallons.

## *Mining*

The metals mining sector includes facilities engaged primarily in exploring for metallic minerals, developing mines, and ore mining. This industry is classified as SIC Major Group 10. The nonmetallic mineral mining and quarrying sector includes mining and quarrying of nonmetallic minerals, except fuels; and establishments engaged primarily in mining or quarrying, developing mines, or exploring for non-fuel, nonmetallic. They are classified under the SIC Major Group 14. (URL: http://www.epa.gov/compliance/assistance/sectors/mineralsmining.html)

Metals mining can significantly impact the water quality of groundwater. The impacts vary depending on the type of ore, mining method, method of ore processing, and the effectiveness of water management. Water quality impacts include erosion and sedimentation, acid rock drainage, cyanide leaching, and dissolution and transport of toxic metals (Dissmeyer, 2000).

Sand and gravel mining can also impact groundwater quality. Removing the protective soil layer makes the groundwater more susceptible to environmental accidents likes spills in the operating pit. Robert Mead (Thurston Co. Public Health, 1995) has studied the more recent environmental impacts from gravel mining. Among other issues, he checked Dept. of Ecology files for hydrocarbon spills in or near gravel mines around the state and found 20 reports in the period 1987-1992. Many of these appear to be associated with USTs or poor housekeeping practices. The report says "excavating above the water table with no associated activities such as vehicle maintenance or asphalt batch plants, causes a relatively low risk to ground water quantity and quality." Mining below the water table causes greater risks. Discussion on the water quantity related impacts of sand and gravel mining is included in the "Water Quantity" section.

During the first half of the 20$^{th}$ century, environmental controls on mining were limited or nonexistent resulting in more than 200,000 abandoned or inactive mines and 60 mines sites in 25 States on the Federal Superfund National Priorities List by 1997 (Dissmeyer, 2000). These include: Bunker Hill (Idaho), Midnite Mine (Washington), and the Eagle Mine (Colorado).

Environmental controls over the mining industry have substantially increased since the first half of the 20$^{th}$ century. Three basic types of laws now regulate the mining industry: The first type defines the areas that are off-limits to mining. The second type defines the methods for allocating mineral deposits for extraction and the third type governs the extraction process and establish restrictions on the types and amounts of wastes that may be generated (U.S. EPA, 1995). Within Washington, mine siting and the subsequent use of the mine are also subject to the State Environmental Policy Act (SEPA) rules. Commonly, groundwater monitoring plans and BMPs are developed as a result of this SEPA process.

## *Wrecking Yards*

Wrecking yards are establishments that engage in auto wrecking; they are included within SIC 5093 (Scrap and Waste Materials). Wrecking yards have a history of contamination in Washington. Site contamination can come from leaving scrap metals and car bodies on the ground surface. This allows metals (and fluids left in the waste materials) to leach out into the unprotected ground surface.

**Table 1.3 List of Contaminants and Causes of Contamination for Different Contaminant Sources/Activities**

| Activity/Source of Groundwater Contamination | | List of Contaminants | Causes of Contamination |
|---|---|---|---|
| Industrial/Commercial Land Uses | | | |
| Underground Storage Tanks (USTs) | | VOCs, other Organics, Arsenic, Barium, Cadmium, Chloride, Lead (Historic) | - Leaks seeping into groundwater<br>- Vapor phase releases may also contaminate groundwater<br>- Spills at fill location seeping to groundwater |
| Above Ground Storage Tanks (ASTs) | | VOCs, other Organics, Arsenic, Barium, Cadmium, Chloride, Lead (Historic) | - Leaks and spills seeping into groundwater |
| Mining | Gravel and Sand | VOCs, other Organics, Turbidity | - Introduces turbidity to nearby wells<br>- Area becomes more vulnerable to spills |
| | Metals | Metals, Cyanide, Organics including VOCs | - Oxidation of ore causes acid mine drainage<br>- The use of surface impoundments for solution extraction, and storm water retention |
| Wood Preserving/Treating | | VOCs, other Organics, Arsenic, Copper, Pentachlorophenol | - Poor operation practices at treatment areas<br>- Uncontrolled seepage of contaminated storm water in areas used for drying |
| Wrecking Yards | | VOCs, other Organics, Lead, Copper, Chromium, Barium | - Rupture of vehicle tanks<br>- Battery leaks to groundwater<br>- Leaching of metals as vehicles rust |
| Processing, Storage, and Disposal of Radioactive Waste | | VOCs, other Organics, Arsenic, Barium, Lead, Chromium, Cadmium, Mercury, Selenium, Nitrate, Nitrite, TSS | - Spills at processing and storage sites<br>- Leachate reaching groundwater |
| Pipelines (Hazardous Liquid Transmission) | | Organics including VOCs | - Leaks from pipe seeping into groundwater |
| Hydrocarbon Extraction | | VOCs, other Organics, Sodium Chloride, Chlorides, Acids, TSS, Chromium | - Disposal of waste fluids (often to ponds)<br>- Treatment of wells to enhance recovery |
| Municipal/Residential Land Uses | | | |
| Landfills | Solid Waste<br>Hazardous Waste | VOCs, other Organics, Arsenic, Barium, Lead, Chromium, Cadmium, Mercury, Nitrate, Nitrite, Selenium, TSS | - Leachate reaching groundwater |
| Storm Water Runoff/Added Impervious Surfaces | | Organics, Coliform Bacteria, Lead, Chromium, TSS | - Runoff carrying sediments or contaminants getting into groundwater |
| Golf Courses | | Organics and Pesticides, Nitrate, Nitrite, Phosphorus, Metals, Turbidity | - Improper application of household products<br>- Field leaching or infiltration of fertilizers and pesticides<br>- Runoff into groundwater |
| On-Site Sewage (Septic) Systems | | Nitrate, Nitrite, Phosphorus, Bacteria, Viruses, Organics (Solvents, Petrochemicals, Pesticides), Metals, Turbidity | - Inadequate design, inappropriate installation, neglectful maintenance and use<br>- Exhausted life expectancy, inappropriate siting<br>- High density of septic systems may overwhelm dilution capabilities of groundwater for nitrate |
| Cemeteries | | Nitrate, Nitrite, Phosphorus, Bacteria, Viruses, Organics including VOCs and Pesticides, Metals, Turbidity | - Field leaching or infiltration of fertilizers and pesticides<br>- Decomposing bodies may contaminate groundwater |
| Miscellaneous | | | |
| Abandoned Wells | | Varies | - Spills of contaminants into groundwater |

Note: The listed causes of contamination are based on historic reports. Recent regulations have addressed many of the concerns surrounding historic causes of contamination.

Wrecking yards are subject to all the regulations associated with hazardous waste storage and disposal. To address the need for facility specific guidance, the WA State Dept. of Ecology developed a set of best management practices (BMPs) on "Preventing Storm water Pollution at Vehicle Recycler Facilities" to try to prevent future contamination at wrecking yards (WDOE 94-146). Unfortunately, there continue to be new instances of contamination related to wrecking yard practices, with nine auto wrecking facilities within King County listed on the February 25, 2003 WA State Dept. of Ecology Hazardous Sites List (URL: http://www.ecy.wa.gov/programs/tcp/mtca_gen/hs030225.pdf).

### *Wood Preserving/Treatment*

Wood treatment facilities, classified within SIC 2491, treat wood by injecting chemicals that will kill insects and other organisms that eat or otherwise damage the wood. Commonly used chemicals in wood treatment/preserving have in the past included creosote, chromated copper arsenate, and pentachlorophenol (PCP).

A number of Superfund sites were contaminated by wood processing facilities, which include:

- American Crossarm & Conduit Co., Chehalis
- Wyckoff Co./Eagle Harbor site, Bainbridge Island

Besides being subject to all the regulations associated with hazardous waste storage and disposal, these facilities are required to have a drip pad, tank, or container to accumulate all of the hazardous waste generated (Resource Conservation and Recovery Act (RCRA) subtitle C subpart W).

Compliance with these regulations is necessary to protect groundwater from contamination. An investigation was done by Region 7 of the U.S. EPA in 2000 to evaluate the effectiveness of the existing regulations. The investigation found significant non-compliance issues in wood treatment/preserving facilities. Violations observed at the facilities included but were not limited to:

- failure to make hazardous waste determinations (40 CFR 262.11);
- failure to notify of hazardous waste activity (40 CFR 262.12(a));
- illegal treatment, storage, and/or disposal of hazardous wastes (RCRA §3005, 40 CFR 262.34(a) and (b));
- failure to handle hazardous wastes in such a manner as to minimize the possibility of release into the environment (40 CFR 265.31); and/or
- failure to comply with drip pad regulations (40 CFR 265 Subpart W) (U.S. EPA, 2000e).

This type of investigation has not been performed in King County, thereby limiting the usefulness of these finding. They do, however, indicate that problems are still common with wood preserving facilities.

### *Processing, Storage and Disposal of Radioactive Waste*

The use of radioactive materials and generation of radioactive waste takes place in a number of different commercial/industrial activities. The WA Dept of Health classifies radioactive material users into three broad user groups: medical, industrial (radiography, fixed & portable gauges), and laboratory.

The processing of radioactive waste typically involves reducing the volume of the water, solidifying non-solid wastes to make them physically stable, and packaging the waste to isolate it from the environment. Storage of radioactive waste is usually done to either allow the waste to decay to a lower radioactive level, to temporarily hold waste awaiting processing, or to temporarily hold waste awaiting disposal in an approved facility.

Historically, most of the radionuclides that have been observed in drinking water sources are naturally occurring (U.S. EPA, 2000f). Of particular concern are naturally occurring uranium and naturally occurring radium isotopes, radium-226 and radium-228. Anthropogenic releases of radioactive waste are primarily the result of improper waste storage, leaks, or transport (U.S. EPA, 2000f). Once the radionuclides are released, they can migrate down to the groundwater. Transport of radioactive contaminants in the subsurface is difficult to predict because they are influenced by radioactive decay in addition to the nonradiogenic processes (Freeze and Cherry, 1979).

The U.S. Department of Energy (U.S. DOE) is responsible for radioactive waste related to nuclear weapons production and certain research activities. The Nuclear Regulatory Commission (NRC) allows Washington to regulate both radioactive materials and commercial radioactive waste. Within Washington, the WA DOH Division of Radiation Protection regulates radioactive materials and wastes. Two sections within this division have responsibilities for radioactive materials, the Radioactive Materials Section, and the Waste Management Section. The later includes the Low-Level Radioactive Waste Program and the Uranium Mills Program. The WA DOH and WA State Dept. of Ecology regulate the commercial low-level radioactive waste disposal site operated by US Ecology, Inc. near Richland, Washington. WA State Dept. of Ecology issues permits for radioactive waste disposal, regulates hazardous waste, and is the landlord of the US Ecology, Inc. site.

### *Pipelines (Hazardous Liquid Transmission)*

A transmission pipeline is defined under WAC 173-180A-030 as a pipeline subject to regulation by the U.S. Dept. of Transportation under 49 CFR 195 through which oil moves in transportation, including line pipes, valves, and other appurtenances connected to line pipe, pumping units, and fabricated assemblies associated with pumping units. The pipeline transportation of hazardous liquids is classified within SIC Major Group 46. In Western Washington there are several pipelines that carry fuel materials (gasoline, diesel, kerosene) from refineries to distribution centers in the major cities where the fuels are used. The main such pipeline is located along the main population centers in the Puget Sound region and further south to Portland. Pipelines are considered to be the safest form of energy transmission (U.S. DOT, 2003).

Past pipeline spills within Washington have involved a range of different volume releases (from <1000 to over 400,000 gallons). These have resulted from a wide variety of sources and causes related to pipelines (WA State Dept. Ecology, 1997). One spill in 1996, for instance, released ~1500 gallons from a small crack in the Olympia Pipeline into a slough near Everett. It is believed that construction damage during the original installation in 1972 was the cause (WA State Dept. Ecology, 1997). A release in King Co., the Maplewood leak in Renton, resulted in groundwater contamination. The release was not detected immediately since the release rates were below the capabilities of the engineered detection systems.

There has been a strong connection between the instances of pipeline spills and the subsequent expansion of state regulations on spill prevention and response. Because of the wide variety of specific sources and causes, it is difficult to measure the effectiveness of state spill prevention endeavors (WA State Dept of Ecology, 1997).

### *Hydrocarbon Extraction*

The extraction of oil and gas involves four major processes: (1) exploration; (2) well development; (3) production; and (4) site abandonment. It is classified as SIC Major Group 13.

Contamination problems associated with oil and gas extraction mainly involve the other fluids (usually saline water) that occur in the same reservoir formations as the hydrocarbons. Produced water during extraction is usually a highly saline brine accompanied by trace contaminants inherent in the reservoir (Dissmeyer, 2000). Disposing of these co-produced materials is often difficult, with Type II underground injection wells and waste pits being accepted methods (Dissmeyer, 2000).

The WA State Dept. of Natural Resources, through the Division of Geology and Earth Resources, regulates drilling and related activities and production of hydrocarbons under the Oil and Gas Conservation Act and the Department of Natural Resources rules (Chapter 78.52 RCW and Chapter 344-12 WAC).

Outstanding concerns associated with hydrocarbon extraction include:

- Improper plugging of abandoned wells;
- Direct injection of produced waters into groundwater;
- Wells that aren't cased or sealed, or where the casing or grouting fails; and
- Failure of waste pits allowing contaminants to migrate through soil to shallow aquifers (Dissmeyer, 2000).

### *Landfills*

Landfills are used for the disposal of waste. They have a history of polluting groundwater within King County, the state of Washington, and throughout the U.S. In King County, two former landfills are on the U.S. EPA list of Superfund sites: Seattle's Kent Highlands LF and Midway LF.

Groundwater contamination from landfills generally occurs when liquids are released from the landfill. This involves one of the following (Tindall and Kunkel, 1999):

- Disposal of liquid industrial wastes, oil, solvents or other chemicals; and
- Release of contaminants from disposed solids to precipitation water that percolates through the landfill materials (leachate).

The regulatory measures for landfills have developed as the understanding on the weaknesses of the design has evolved. Modern landfills are well-engineered facilities that are located, designed, operated, monitored, closed, cared for after closure, cleaned up when necessary, and financed to insure compliance with federal, state, and local regulations.

Historically, free liquids were occasionally disposed in landfillsleading to widespread contaminant plumes that was often discovered only when the contamination showed up in off-site drinking water wells. These instances prompted Washington to add new regulations (Minimum

Functional Standards for Solid Waste Handling, WAC 173-304) to prevent these occurrences in the future.

Future leachate problems could be largely prevented through the application of these Minimum Functional Standards. New landfills are required to have their cells lined with an impermeable containment barrier (generally a plastic membrane) and to have a secondary containment with a leachate collection system. Both new as well as former landfills are required to have impermeable caps to prevent rainfall from penetrating the landfill materials. Such engineering precautions have made landfills much safer since the Minimum Functional Standards were imposed. Occasional failures still occur due to unanticipated factors. Recent research has looked at groundwater contamination occurring indirectly when vapor transport from the landfill apparently was resolubilized into groundwater without an intervening liquid transport mode.

The remaining issues with landfills can be eliminated by carefully restricting the nature of the wastes to be disposed in the landfill. It is probably impossible in a municipal landfill system to ensure compliance with these restriction.. Certain classes of waste, however, can A landfill disposing construction debris, for example, can ensure that few hazardous wastes will be present in its receiving waste stream.

### *Golf Courses*

The use of fertilizers and pesticides on landscaped lands can contribute to groundwater pollution, and some examples of heavily landscaped areas include golf courses, residential yards, commercial yards, ball fields, and parks (U.S. EPA, 2001c). A pesticide is any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest. Pests can be insects, mice and other animals, unwanted plants (weeds), fungi, or microorganisms like bacteria and viruses. Though often misunderstood to refer only to insecticides, the term pesticide also applies to herbicides, fungicides, and various other substances used to control pests. Under United States law, a pesticide is also any substance or mixture of substances intended for use as a plant regulator, defoliant, or desiccant (U.S. EPA, 2003).

The physical and chemical properties that make pesticides effective for pest control also add to their potential for groundwater contamination. Pesticides have two properties, persistence and adsorption, that control their fate after application to the soil. The persistence relates to a pesticide’s ability to degrade over time so pesticides that are highly persistent (i.e., don’t degrade quickly) pose the highest threat to groundwater. Adsorption refers to the pesticides ability to bind to soil particles after application. However, many pesticides have a high adsorption potential and low solubility in water, making them less of a contamination risk to groundwater (Mahler et al., 2002).

Fertilizers are organic and inorganic materials added to soil to supply nutrients for plant growth. Fertilizers that contain nitrogen, potassium, and phosphorus are commonly used, and regardless of the form of nitrogen added - chemical fertilizer, an organic mix, manure, or sewage sludge - soil organisms convert it to nitrate before plants take it up.

Pesticides most commonly leach to groundwater in areas with permeable soils and high water table surfaces (Teso et al., 1996). Studies specific to application of pesticides to turfgrass have shown that leaching can be a problem on sandy soils when a rainstorm or heavy irrigation occurs in the first few days after application (CSU, 1993). It has also been documented that improper or excessive use of nitrogen fertilizer on golf courses can lead to nitrate pollution of groundwater

(Wong et al., 1998; CSU, 1994). Fertilizer applicators can minimize this problem by implementing Best Management Practices for fertilizer use (CSU, 1994). King County has a manual titled "Best Management Practices for Golf Course Development and Operation" that is specifically directed at the minimizing the impacts of pesticide and fertilizer use on golf courses (King County, 1993).

A recent trend in the land-use management literature is to assess the vulnerability of groundwater to pesticides and fertilizers by combining aquifer susceptibility, the chemical properties of the pesticides and fertilizers, and the application rates and timing of these chemicals (Teso et al., 1996; Shukla et al., 1998; Tucker et al., 2000). These methods might be used to develop BMPs for King County golf courses to protect the groundwater from degradation.

### *Addition of Impervious Surface/Storm Water Runoff*

Storm water runoff is increased from the addition of impervious surfaces and can adversely affect groundwater quality through the introduction of contaminants and sediments that accumulate on impervious surfaces. The U.S. EPA (2001b) reports that 77 of the 127 priority pollutants have been detected in urban runoff nationwide. The presence of pollutants makes water quality treatment of storm water runoff necessary.

Studies conducted under the U.S. EPA indicated detention and retention basins to be the most effective and reliable of the techniques examined for control of urban runoff pollutant loads (U.S. EPA, 1987). King County currently manages its storm water runoff in the "King County, Washington, Surface Water Design Manual" (King County, 1998). This manual requires that storm water be treated in a constructed facility before infiltration when certain criteria are met. The routing of storm water into infiltration systems is the preferred method for storm water management in Washington and a number of literature sources have been compiled demonstrating that they can be effective in providing contaminant removal (Barrett, 2002; Potts, 2002; U.S. EPA, 2000).

The management of storm water runoff can also affect the quantity of recharge to the aquifer. More discussion on this topic can be found in the "Water Quantity" section.

### *On-site Sewage (Septic) Systems*

On-site sewage systems (OSS) are used to treat and dispose of sanitary waste. Common failures of OSSs in the past have included unpumped and sludge-filled tanks, which result in a clogged adsorption field, and hydraulic overloading caused by increased occupancy and greater water use following installation of new water lines to replace wells and cisterns (U.S. EPA, 2002). A number of household chemicals have also been found to interfere with the proper operation of the septic system, which allows them to pass through into the aquifer, untreated (U.S. EPA, 2002).

Bacterial and viral pathogen contamination from OSSs can be prevented through proper siting, maintenance, and use. The Washington Dept. of Heath (WA DOH) currently develops and implements standards for the performance, application, design, operation, and maintenance of on-site sewage treatment and disposal systems to prevent bacterial and viral pathogen contamination to groundwater. In King County, Seattle & King Co. Public Health is responsible for permitting new OSSs. Public Health has developed siting and design criteria for OSSs as identified in Title 13 of the Board of Health code. Remaining contaminants such as nitrates, chlorides, and any organic solvents placed in the system usually depend on dilution to protect groundwater. The main outstanding issue associated with the design of OSSs is the nitrogen removal capacity.

Upon release from the septic tank, most of the nitrogen is in the form of ammonia. This ammonia gets converted by aerobic bacteria in the biomat and upper vadose zone to nitrite and then nitrate, which is a major groundwater pollutant (U.S. EPA, 2002). Nitrate concentrations can be reduced by dilution or denitrification. Denitrification requires both anaerobic conditions and an available electron donor, like carbon or sulfur. Without this process, the reduction of nitrate concentrations relies entirely on dilution through dispersion or recharge of groundwater supplies by precipitation (U.S. EPA, 2002).

A high density of septic systems will reduce the ability to dilute the nitrate levels sufficiently. A WA DOH (2002) technical report suggests it could be necessary to either increase the minimum lot size to 0.5 - 1.0 acres or add additional treatment for nitrogen at high-risk sites within Washington to prevent nitrate contamination to groundwater. Following the method of Hantzsche and Finnemore (1993), a mass balance equation was used to determine the minimum lot size necessary given different rainfall recharging rates over a development. Their method considers inputs of nitrate from wastewater and rainfall recharge and losses due to denitrification in the soil column and upper portion of the aquifer. Requiring the nitrate levels reach no more than half the drinking water limit, or 5 mg/L gives:

$$A = \frac{0.01344\, W\left[n_w - dn_w - 5\right]}{R(5 - n_b)}$$

where A is lot size in acres (average over the area of concern); W is average daily wastewater flow per lot in gallons; R is the recharge rate in inches/yr; $n_w$ is the effluent nitrate level, in mg/L; $n_b$ is the nitrate levels, in mg/L, contained in the recharge from rainfall; d is the fraction lost by denitrification; and 0.01344 is a conversion factor having units of acre inch day per lot $yr^{-1}$ $gal^{-1}$.

The values chosen as inputs to this equation are in the table below:

| Parameter | Typical Range | Value(s) Used | Source |
|---|---|---|---|
| W | 50-70 gal/day per person | 240 gal/day | U.S. EPA (2002) |
| $n_w$ | 20-100 mg/L | 30-40 mg/L | U.S. EPA (2002) |
| $n_b$ | 0.5-1.0 mg/L | 1 mg/L | Hantzsche and Finnemore (1993) |
| d | 0-0.75 | 0.2 | Hantzsche and Finnemore (1993) |

An average daily wastewater flow per lot of 240 gal/day was used since it represents the minimum design flow required by the WA State Dept. of Health for single home on-site septic systems. The U.S. EPA (2002) estimates average daily flows of 40-60 gal/person/day.

The main assumption used in this method is uniform and complete mixing of wastewater and percolating rainfall over the entire developed area, which is completed at the water table. Since this method ignores any dilution effects of lateral groundwater inflow from upgradient areas, it is considered to be conservative. Using a probable range for rainfall recharge rates in King County's CARAs of 15-25 inches/year (Bidlake and Payne, 2001) indicates the need for a minimum average lot size of ~1 acre. If effluent nitrate levels were reduced significantly, to around 10 mg/L, additional restrictions on lot size would be unnecessary.

It should be noted that this methodology is only appropriate to evaluate the need for increased lot size to dilute elevated nitrate levels in densely populated areas. It should not be used as justification for reducing the minimum lot size. The current minimum lot size requirements were developed to ensure bacterial and viral pathogen removal before the effluent reaches the groundwater.

### *Cemeteries*

A number of studies have linked groundwater contamination to cemetery leachate originated from human corpses (Spongberg and Becks 1999, Pasheco and others 1991). Amid concern about cemeteries' impacts to groundwater, the World Health Organization (WHO) published a scientific literature review on the subject. The high concentrations of naturally occurring organic and inorganic substances at cemeteries suggest categorizing them as a special kind of landfill. The unsaturated zone beneath the burial site acts as a filter and absorbant of bacteria, pathogens, and viruses. The ability of contaminants to survive in the unsaturated zone depends on the soils and depth to groundwater, with fine-grained soils and deep groundwater levels being preferable.

The WHO (1998) has made recommendations on the best ways to prevent contamination from cemetery leachate. These siting and design of cemetery recommendations follow the direction taken by the United Kingdom Parliament and specify:

1. Human or animal remains must not be buried within 250 meters (~820 feet) of any well, borehole, or spring from which a potable water supply is drawn.

2. The place of interment should be at least 30 meters (~98 feet) away from any other spring or watercourse and at least 10 meters (~33 feet) from any field drain.

3. The base of burial must be at least one meter (~3.3 feet) above solid rock.

4. The base of all burial pits on the site must maintain a minimum of one meter (~3.3 feet) of clearance above the highest natural water table.

5. Burial excavation should be backfilled as soon as the remains are interred, providing a minimum of one meter (~3.3 feet) of soil cover at the surface.

## Water Quantity

Under the Growth Management Act (RCW 36.70A(1)), protection of the quality and quantity of groundwater used for public water supplies must be addressed within a County's comprehensive plan. Within King County, local governments have adopted a countywide planning policy (CA-5) requiring adoption of measures to protect both the quality and quantity of groundwater. Water quantity issues revolve around both availability of water for potable use and availability of water for discharge to support base flow in streams and other surface water bodies. The human activities that can potentially have adverse impacts on water quantity are listed below:

- Addition of Impervious surfaces
- Vegetation removal
- Groundwater extraction
- Sewer lines
- Sand and Gravel Mining

The addition of impervious surfaces can have a large impact to groundwater recharge by changing the local water balances and volumes and decreasing baseflow components (Holman-Dodds et al., 2003). The use of low impact, infiltration based, development (LID) in storm water management can offset the losses of recharge, and in some cases completely eliminate the losses due to impervious surface additions (Konrad and Burges, 2001; Holman-Dodds et al., 2003). A more detailed discussion on the elements of LID can be found in "Low Impact Development (LID) – A Literature Review" (U.S. EPA, 2000). It should be noted that increasing impervious surfaces does not necessary lead to decreases in recharge or baseflow. For example, if a forested area is replaced with a paved surface for which runoff is collected in a recharge pond, net recharge may be greater than under the original condition in which much of the precipitation is lost to interception and evapotranspiration (Bidlake and Payne, 2001).

Increasing urbanization, which involves both the replacement of soil and vegetation by pavement and buildings and the replacement of natural stream networks by artificial drainage systems, can reduce infiltration, thereby impacting groundwater recharge (Dingman, 2002).

Extracting groundwater through pumping wells changes the natural rates of recharge and discharge, thus having an effect on water quantity (Dingman, 2002). These wells include (in Washington State) wells that the Dept. of Ecology must issue a prior water right under RCW 90.44 and "exempt wells" that do not require a water right. Any extraction from a groundwater well must be balanced by: (1) an increase in recharge caused by the extraction; (2) a decrease in natural discharge; (3) a loss of storage; or (4) a combination of these factors (Domenico and Schwartz, 1990). The impact of one well may not be significant to regional aquifer recharge but several hundred wells in a limited aquifer may stress the system and/or locally change the flow direction. When considering the effects of groundwater extraction on water quantity, it is important to remember that not all water pumped is consumed (USGS, 1999). On-site sewage systems will return some of the extracted water back to the groundwater via septic drainfields. A portion of water used for irrigation will also be returned back to the groundwater body (USGS, 1999).

Sewer lines affect water quantity to a local area through both Infiltration and Inflow (I & I) and the export of sewer water to adjacent basins. I&I is both the infiltration of water into the sewer line that occurs when sewer lines are not completely sealed and the groundwater table is above the line and the inflow of water from illicit connections to the sewer line. This infiltration acts as a net loss of groundwater recharge to the local area impacting the available water for withdrawal. King County is in the process of evaluating the impacts of I & I on the whole wastewater system and trying to identify any problematic areas.

The types of water quantity issues related to sand and gravel mining include:

- Loss of water supplies due to breach of an aquifer plug or site water consumption
- Changes in the timing or quantity of discharge from springs (WA State Dept. of Ecology, 2000c; Garland and Liszak, 1995).

In October 1993, mining activities at the High Rock gravel mine near Monroe, WA caused a loss of water supply due to a breach of aquifer plug (Garland, D. and Liszak, J., 1995).

## Monitoring

Groundwater monitoring provides essential data needed to evaluate changes in the resources over time, develop groundwater models, forecast trends, and to design, implement and monitor the effectiveness of groundwater management and protection programs (USGS, 2001). Local, regional, state, and federal agencies all recommend monitoring groundwater to detect possible contaminant sources. The role of groundwater monitoring is to:

- understand the baseline natural quality of the system to detect future impacts;
- have an early warning system on the impacts of pollution sources;
- identify trends in groundwater quality caused by natural events, the impact of diffuse pollution, and changes in the hydraulic regime; and
- collect new data on the aquifer system to improve its conceptual and/or numerical modeling.

The essential components of a groundwater monitoring program need to include: (1) selection of observation wells to provide representative data on geologic, climatic, and land-use environments; (2) determination of the frequency of water-level measurements to adequately characterize the hydrologic behavior of the aquifer; (3) implementation of quality assurance; and (4) establishment of effective practices for data reporting (USGS, 2001).

With respect to monitoring, the WA DOH requires public water systems (PWS) regulated by the Federal Safe Drinking Water Act, "Group A" systems, to record the usage of groundwater on a monthly and yearly basis. Under the WA State Dept. of Ecology's recent metering rule (WAC 173-173), "new and existing ground water rights where the department concludes that the withdrawal of any volume of water may affect surface waters containing depressed or critical salmonid stock" are required to be metered and reported to Ecology.

Group A public supply wells (PWSs) must also test for inorganic parameters (IOC) every three years and for organic parameters (SOC & VOC) once every five years. These results are compared to minimum thresholds as well as state and federal Water Quality Standards (WAC and U.S. EPA; Primary and Secondary drinking water standards). More frequent testing maybe required if any drinking water quality parameter exceeds a threshold and/or water quality standard (see WA DOH protocols for exact details of compliance with drinking water standards). Several Group A PWS also have electronic continuous recorder monitoring the groundwater levels (depth to water) for their groundwater sources. Cities like Issaquah, Renton, and Redmond, also monitor their groundwater sources on a semi-annual or quarterly basis to increase their ability to respond to potential contamination issues.

Monitoring is also a necessary component of WAC 365-195-920, the administrative rule for best available science (Criteria for addressing inadequate scientific information). Since there are limitations in the science that is available at the present time to assure adequate protection of groundwater through the CARA process, the governing GMA regulations WAC 365-195-920 recommend the following:

> (1) A "precautionary or a no risk approach," in which development and land use activities are strictly limited until the uncertainty is sufficiently resolved; and
>
> (2) As an interim approach, an effective adaptive management program that relies on scientific methods to evaluate how well regulatory and non-regulatory actions achieve

their objectives. Management, policy, and regulatory actions are treated as experiments that are purposefully monitored and evaluated to determine whether they are effective and, if not, how they should be improved to increase their effectiveness. An adaptive management program is a formal and deliberate scientific approach to taking action and obtaining information in the face of uncertainty. To effectively implement an adaptive management program, counties and cities should be willing to:

(a) Address funding for the research component of the adaptive management program,

(b) Change course based on the results and interpretation of new information that resolves uncertainties, and

(c) Commit to the appropriate timeframe and scale necessary to reliably evaluate regulatory and non-regulatory actions affecting critical area protection and anadromous fisheries.

An "adaptive management program" referred to in WAC 365-195-920(2) is also required by the governing regulations. This approach would involve:

- Observation of the suspected land uses that could impact groundwater quantity or quality, including management practices that are commonly followed, which would be in compliance with protective practices;
- Monitoring of groundwater (at "sentinel wells") in the vicinity of these uses;
- Monitoring of groundwater in other areas of King County that have similar geology and other environmental (e.g., climate) influences, to provide both background conditions (experimental control) as well as evidence of wider-scale impacts if they occur; and
- Coordination with policy-makers to provide the experimental scenarios that can be monitored, and to feed back the results of the adaptive management into the policy arena.

To be effective and efficient, an adaptive management monitoring program must address the questions that require management. In areas where a particular land use is of concern, the characteristic analytes should be included in the sampling and analysis procedures. Because of the benefits of having a general characterization of the aquifer and its flow regime, water levels, field parameters (i.e., pH, temperature, dissolved oxygen, conductivity, Eh, and turbidity), major ions, and any analytes that have a likelihood to exceed drinking water or environmental standards should be measured. Aquifer parameters should also be measured when possible.

Adaptive management implementation is required to support best available science. As knowledge grows, the ability to manage well depends on being able to make changes. The adaptive management strategy that is proposed will function as long as the recommendations for funding and implementation are carried out including enforcement of protection practices. Some land uses could be permitted with a proviso that their proponents would provide monitoring opportunities and an annual fee to support both the monitoring effort and the review and assessment of the results.

### 6.2.3 Special Areas / Issues of Concern Specific to King County

In order to discern what special issues may be occurring under local conditions, King County has been assessing its groundwater. This assessment includes both direct methods, e.g., sampling groundwater wells and measuring water levels in wells, and compiling information about groundwater quality (and potential contaminant sources) and quantity from other state agencies and groundwater purveyors.

The direct sampling effort, "Ambient Groundwater Monitoring," has indicated that select inorganic compounds arsenic, nitrate, and lead are found at concentrations close to or exceeding drinking water standards (MCLs) in a number of water supply wells around the county. These conclusions have been corroborated by water quality data from Group A sources, as compiled by the WA DOH.

The frequencies over the entire Ambient Monitoring network are:

- Lead: 0 sites with average concentration > 0.0075 mg/L (1/2 the MCL)
- Arsenic: 16 sites with average concentration > 0.005 mg/L (1/2 the MCL)
- Nitrate: 2 sites with average concentration > 5 mg/L (1/2 the MCL)

Arsenic has been found at the greatest frequency in the East King County Groundwater Management Area, i.e., the Snoqualmie River Valley. The arsenic in this area is considered naturally occurring, based on the presence of arsenic-bearing materials in the Western Cascades, with ores high enough that a number of historic mines in the area produced arsenic. This conclusion has been documented in a study by Parsons & Allen-King (2003).

Nitrate is another contaminant of concern in King County, with Vashon-Maury Island (VMI) having the greatest number of elevated nitrate levels. Additional sampling is ongoing on VMI to determine and delineate the extent elevated nitrate levels on the island. The ambient data has indicated an area of higher concentrations in shallow wells on VMI. WA DOH information also points to similar areas of concern (for nitrate) in South King County. Although no specific source of nitrate contamination has yet been determined, future study may focus on a list of potential sources and activities:

- Naturally occurring due to nitrogen fixation (i.e., Alder trees)
- Septic systems
- Overuse of fertilizers
- Poor management of animal wastes

Some of the nitrate concentrations have been shown to be increasing (on VMI) over a long baseline period, based on a comparison between present-day analytical results and the data compiled from the Groundwater Management Plan sampling in 1989-1992.

A study by the USGS, (Erwin and Tesoriero, 1997) predicted nitrate concentrations at different depths and locations throughout the Puget Sound Basin, based on a regression analysis of measured concentrations in domestic water supply wells and the land use (urban, forest, or agriculture), depth to water, and geology. The regression shows Vashon having the lowest likelihood (less than 10 percent probability) for ≥ 3 mg/l nitrate at a depth of 50 feet. The ambient monitoring results show 2 wells (out of 22) which exceed 3 mg/l, and these have depths of 67 feet and 80 feet, some of the shallowest sampled in the area. The paper predicts that much higher concentrations of nitrate may be present under urban or fully developed areas in King County.

Lead has also been detected in several wells across the County. The data are not consistent among samples from the same wells, so it is expected that this is an artifact of the sampling process (through existing plumbing).

Three other inorganic compounds, iron, manganese, and sodium, were also measured at concentrations above their drinking water standards. The iron and manganese have secondary standards that are based on esthetic (taste or color) considerations rather than concerns for health. Sodium can be a health concern to some individuals.

A map was also derived, from anecdotal information from Seattle & King County Public Health investigators, of areas in King County that have problems for water supply. These problems include:

- low water quantity (or excessive depth to reach it);
- iron, manganese, sulfate, or arsenic (or other high mineral content); and
- possible salt water intrusion from the Sound (on Vashon Island).

The King County Department of Natural Resources and Parks (DNRP) has also obtained a number of GIS data sets (mainly from WA State Dept. Ecology) of potential (or known) sources of contamination. These areas and chemicals of concern may be further investigated in the future as part of the DNRP Groundwater Protection Program monitoring effort.

Water quantity related issues within King County include the reduction of base flows in Rock Creek, Bear Creek, and North Fork Issaquah Creek as a possible result of neighboring groundwater withdrawals. Also recent reports indicate a number of wells in south Auburn are going dry. The cause of the wells going dry is uncertain at this time.

# 6.3 CONCLUSION

Mapping Critical Aquifer Recharge Areas provides the general framework within which to base groundwater quality and quantity protection policy. The methods of identifying critical aquifer recharge areas have evolved substantially in the resource management and land-use planning literature over the last 25 years. The most recent advancement in prioritizing aquifer recharge areas was presented in this chapter and requires two major tasks. The first task is to map the aquifer susceptibility, based on a simplified representation of the hydrogeologic transport phenomena. The second task is to map the areas where the value of the resource is high. The most common areas mapped for this second step are water supply protection areas (commonly called wellhead protection areas and sole source aquifers). The final overlay of these two maps identifies the critical aquifer recharge areas.

There are many land-use activities that can potentially affect the quality or quantity of groundwater recharge. Any potential land-use activity that stores, uses, or produces known contaminants of concern (constituents found to be a risk to human health and capable of groundwater transport) and has a sufficient likelihood of releasing such contaminants to the environment at detrimental levels is considered a threat. Any land-use that can reduce the quantity of recharge to the aquifer to a significant degree is also considered to be a threat. If these activities occur above aquifer recharge areas critical to groundwater quality and quantity, it is prudent to implement groundwater protection measures in those areas to protect the groundwater resources of the County.

Adaptive management implementation is required to support best available science in CARA protection. To be effective and efficient, an adaptive management monitoring program needs to continually identify and address the land-uses that require additional management. And, as knowledge grows, the ability to manage will depend on being able to make changes to policies and their application.

## 6.4 LITERATURE REFERENCES

Aller, L., T. Bennet, , J.H. Lehr, and R.J. Petty. 1987. DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings. U.S. EPA Report 600-2-85-018.

Alley, W.M., T.E. Reilly, and O.L. Franke. 1999. Sustainability of Ground-Water Resources. (U.S. Geologic Survey: Circular 1186).

Barrett, Michael, “Re: Risk of GW contamination from infiltration BMPs.” E-mail to Multiple recipients of list. 20 Dec 2002.

Bekesi, G. and J. McConchie. 2002. The use of aquifer-media characteristics to model vulnerability to contamination, Manawatu region New Zealand. *Hydrogeology Journal* 10(2): 322–331.

Bidlake, W.R. and K.L. Payne. 2001. Estimating recharge to ground water from precipitation at Navel Submarine Base Bangor and Vicinity, Kitsap County, Washington. U.S. Geological Survey Water-Resources Investigation Report 01-4110.

Burgess, D.B., and S.W. Fletcher. 1998. Methods used to delineate groundwater source protection zones in England and Wales. Groundwater Pollution, Aquifer Recharge and Vulnerability (Robins, N S, ed.). Geological Society Special Publication 130, London, England, pp. 199-210.

Cleary, T.C.B.F and R.W. Cleary. 1991. Delineation of Wellhead Protection Areas: Theory and Practice, *Water Science and Technology* 24(11): 239-250.

Colorado State University Cooperative Education. Agricultural Chemicals and Groundwater Protection. 1993. Turf BMP Fact Sheet.

Colorado State University Cooperative Education. Best Management Practices for Nitrogen Fertilization. 1994. Bulletin #XMC-172

Dai, F.C., C.F. Lee, and X.H. Zhang. 2001. GIS-based geo-environmental evaluation for urban land-use planning: a case study. *Engineering Geology* 61 (4): 257-271.

Dingman, S.L. 2002. Physical Hydrology. Prentice-Hall, Inc. Upper Saddle River New Jersey. p. 382.

Dissmeyer, G.E. (Editor). 2000. Drinking Water from Forests and Grasslands – A Synthesis of the Scientific Literature. U.S. Department of Agriculture, Forest Service, Southern Research Center, General Technical Report SRS-39.

Ducci, D., 1999. GIS techniques for mapping groundwater contamination risk. *Natural Hazards* 20(2-3): 279-294.

Erwin, M.L. and A.J. Tesoriero. 1997. Predicting Ground-Water Vulnerability to Nitrate in the Puget Sound Basin, USGS Fact Sheet 061-97, June 1997.

Fagnan, N., R. Lefebvre, E. Boisvert, and Y. Michaud. 1998. Evaluation of Groundwater Vulnerability to Contamination in the Laurentian Piedmont Using the Drastic Method. University of Quebec. INRS – Georesources. 215 p. (In French)

Foster, S., R. Hirata, D. Gomes, M. D'Elia, and M. Paris. 2002. Groundwater Quality Protection. The World Bank. Washington, D.C.

Fritch, T.G, C.L. McKnight, J.C. Yelderman Jr, S.I. Dworkin and J.G. Arnold. 1999. A predictive modeling approach to assessing the groundwater pollution susceptibility of the Paluxy Aquifer, Central Texas, using a Geographic Information System. *Environmental Geology* 39 (9): 1063-1069.

Fritch, T.G, C.L. McKnight, J.C. Yelderman Jr, et al. 2000. An aquifer vulnerability assessment of the Paluxy aquifer, central Texas, USA, using GIS and a modified DRASTIC approach. Environmental Management 25(3): 337-345.

Garland, D. & Liszak, J. "The High Rock Aquifer Break of October 1993." WA State Dept. of Ecology, NWRO. Technical Memorandum. December 1995.

Holman-Dodds, J.K., A.A. Bradley, and K.W. Potter. 2003. Evaluation of hydrologic benefits of infiltration based urban storm water management. Journal of the American Water Resources Assocation 39(1): 205-215.

Ireland Department of the Environment. 2001. Policy and Practice for the Protection of Groundwater in Northern Ireland. Environment and Heritage Services Printing Unit

King County. 1995. Mapping Aquifer Susceptibility to Contamination in King County. King County Dept. of Development and Environmental Services, Seattle, WA.

King County. 1993. Best Management Practices for Golf Course Development and Operation. King County Environmental Division, Seattle, WA.

Konrad, C.P. and S.J. Burges. 2001. Hydrologic Mitigation using On-Site Residential Storm-Water Detention. Journal of Water Resources Planning and Management 127(2): 99-107.

Lobo-Ferreira J.P. and M.M. Oliveira. 1997. Drastic Groundwater Vulnerability Mapping of Portugal. "Groundwater: An Endangered Resource," Proceedings of Theme C 27th Congress of the International Association for Hydraulic Research, San Francisco, USA, Aug. 10-15. pp. 132-137.

Lynch, S.D., A.G. Reynders, and R.R. Schulz. 1993. Preparing input data for a national-scale groundwater vulnerability map of Southern Africa, in 6th National Hydrological Symposium, SANCIAHS, Sept. 1993 and Water S.A.) 20: 239-246, Pietermaritzburg, South Africa. 1994.

Mahler, R.L., H.W. Homan, and G.P. Carpenter. 2002. Pesticides and their Movement in Soil and Water. Quality Water for Idaho Current Information Series No. 865. University of Idaho Cooperative Extension System.

Menani, M. R., 2001. Evaluating and mapping the groundwater pollution susceptibility of the El Madher alluvial aquifer, Eastern Algeria, using the Drastic method. Science et changements planétaires / Sécheresse. 12(2): 95-101.

Merchant, J.W. 1994. GIS-Based Groundwater Pollution Hazard Assessment - A Critical-Review of The Drastic Model. Photogrammetric Engineering & Remote Sensing 60 (9): 1117-1128.

Napolitano, P. and A.G. Fabbri. 1996. Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resouces Management (Proceedings of the Vienna Conference, April 1996). IAHS Publ. No.235, pp. 559-566.

Navulur, K.C.S. and B.A. Engel. 1998. Groundwater vulnerability assessment to non-point source nitrate pollution on a regional scale using GIS, T ASAE 41 (6): 1671-1678. Office of Community Development (OCD), "Model Code Recommendations for Designating and Protecting Critical Areas" (1st ed., 2nd draft, May 2002b).

Otto, C.J., L.E. Bates, G. Bartle, C. Johnston and T. Power. 2000. Development of a hydrogeological database and groundwater vulnerability assessment using GIS and integrated modeling, Garden Island, WA. Progress Report: Hydrogeological Investigation. CSIRO Land and Water.

Pacheco, A., J.M.B. Mendes, T. Martins, S. Hassuda, and A.A. Kimmelmann. 1991. Cemeteries – a potential risk to groundwater. Water Science and Technology 24(11): 97-104.

Parsons, J. Richelle, and M. Allen-King. 2003. "A Geologic Source of Arsenic in Washington State Ground Water: A Literature Review" Poster at 4th Symposium on the Hydrogeology of Washington State, Tacoma, April 8-10, 2003.

Potts, A. 2002, Dec 13. "Risk of GW contamination from infiltration BMPs." E-mail to Multiple recipients of list.

Redmond – Bear Creek Valley Ground Water Management Committee. 1999. Redmond-Bear Creek Valley Groundwater Management Plan: Management Strategies.

Shahid, S., 2000. A study of groundwater pollution vulnerability using DRASTIC/GIS, West Bengal, India. Journal of Environmental Hydrology 8(1).

Shukla S., S. Mostaghimi, and V.O. Shanholtz. 1998. A GIS-based modeling approach for evaluating groundwater vulnerability to pesticides. Journal of the American Water Resources Association 34(6): 1275-1293.

Spongberg, A.L. and P.M. Becks. 2000. Inorganic soil contamination from cemetery leachate. Water, Air and Soil Pollution 117: 313-327.

Standard Industrial Classification Manual. 1987. URL: http://www.osha.gov/cgi-bin/sic/sicser5

Stark S.L, J.R. Nuckols, and J. Rada. 1999. Using GIS to investigate septic system sites and nitrate pollution potential. Journal of Environmental Health 61(8):15-22.

Stempvoort, V., D., L. Ewert, and L. Wassenaar. 1992. AVI: A method for groundwater protection mapping in the Prairie Provinces of Canada. Prairie Provinces Water Board, Regina, Saskatchewan.

Swanson, R. D. 1992. Methods to determine wellhead protection areas for public supply wells in Clark County, Washington, Intergovernmental Resource Center, p.37.

Teso, R.R., M.P. Poe, T. Younglove, and P.M. McCool. 1996. Use of logistic regression and GIS modeling to predict groundwater vulnerability to pesticides, Journal of Environmental Quality 25: 425-432.

Thurston Co. Public Health, 1995 "The Direct & Cumulative Effects of Gravel Mining on Ground Water Within Thurston County, Washington."

Tindall, J.A., and J.R. Kunkel. Unsaturated zone hydrology for scientists and engineers. Prentice-Hall, Inc. Upper Saddle River New Jersey. p 331.

Tucker M.A., D.L. Thomas, D.D. Bosch, et al., 2000. GIS-based coupling of GLEAMS and REMM. Hydrology: I. Development and sensitivity, T ASAE 43 (6): 1525-1534.

U.S. Department of Transportation. 2003. Pipeline Safety Statistics. Research and Special Programs Administration - Office of Pipeline Safety. URL: http://www.pipeline101.rspa.dot.gov/pipelineInfo/statistics.htm

U.S. Environmental Protection Agency. 1986. Methodology for analysis of detention basins for control of urban runoff quality, EPA 440-5-87-001.

U.S. Environmental Protection Agency. 1993. Guidelines for delineation of wellhead protection areas, EPA 440-5-93-001; update of same document produced in 1987 (EPA 440/6-87-010).

U.S. Environmental Protection Agency. 1995a. Fact sheets and the citizen's guide to pest control and pesticide safety, EPA 730-K-95-001.

U.S. Environmental Protection Agency. 1995b. Sole Source Aquifer Designation, EPA 440-9-95-001; update of same document produced in 1987 (EPA 440/6-87-003).

U.S. Environmental Protection Agency. 1997. State Source Water Assessment and Protection Programs, EPA 816-R-97-009.

U.S. Environmental Protection Agency. 2000. Low impact development (LID) – A literature review, EPA 841-B-00-005.

U.S. Environmental Protection Agency. 2001a. Source Water Protection Practices Bulletin – Managing above ground storage tanks to prevent contamination of drinking water, EPA 916-F-01-022.

U.S. Environmental Protection Agency. 2001b. Source Water Protection Practices Bulletin – Managing storm water runoff to prevent contamination of drinking water, EPA 816-F-01-020.

U.S. Environmental Protection Agency. 2001c. Source Water Protection Practices Bulletin – Managing turfgrass and garden fertilizer application to prevent contamination of drinking water, EPA 816-F-01-029.

U.S. Environmental Protection Agency. 2001d. Source Water Protection Practices Bulletin – Managing Underground Storage Tanks to Prevent Contamination of Drinking Water, EPA 816-F-01-023.

U.S. Environmental Protection Agency. 2001e. Fact Sheet – Wood Preserving Industry, Downloaded from the web on August 22, 2003. URL: http://www.epa.gov/Region7/waste/pdf/factsheet.pdf.

U.S. Environmental Protection Agency. 2001f. Technical Fact Sheet – Final Rule for (Non-Radon) Radionuclides in Drinking Water, EPA 816-F-00-013.

U.S. Environmental Protection Agency. 2002. Onsite Wastewater Treatment Systems Manual, EPA 625-R-00-008.

U.S. Environmental Protection Agency. 2003a. "Pesticides – about pesticides." Downloaded from the web on July 24, 2003. URL: http://www.epa.gov/pesticides/about/index.htm

U.S. Environmental Protection Agency. 2003b. Potential sources of drinking water contamination index, documentation from webpage: http://www.epa.gov/safewater/swp/sources1.html#COMM

U.S. Geological Survey. 2001. Ground-water-level monitoring and the importance of long-term water-level data. U.S. Geological Survey Circular 1217.

U.S. Geological Survey. 1999. Sustainability of ground-water resources. U.S. Geological Survey Circular 1186.

U.S. Geological Survey. 2002. Assessing Ground-Water Vulnerability to Contamination: Providing Scientifically Defensible Information for Decision Makers. U.S. Geological Survey Circular 1224.

Washington State Dept. of Ecology. 1997. Oil Spills in Washington State: A Historical Analysis (Pub #97-253).

Washington State Dept. of Ecology. 2000a. Guidance Document for the Establishment of Critical Aquifer Recharge Area Ordinances (Pub #97-30, K. Cook, revised July 2000).

Washington State Dept. of Ecology. 2000b. Occurrence of Methyl Tertiary-Butyl Ether (MTBE) in Groundwater at Leaking Underground Storage Tank Sites in Washington. (Pub #00-09-054)

Washington State Dept. of Ecology. 2000c. Maury Island Gravel Mining Impact Studies – Final Fact Sheet. (Pub #00-09-005).

Washington State Dept. of Health. Source Water Assessment Program (SWAP), documentation from webpage: http://www.doh.wa.gov/ehp/dw/our_main_pages/swap.htm. 2003.

Washington State Dept. of Health. Rule Development Committee Issue Research Report – Lot size (minimum land area), August 2002, downloaded 7/14/03: http://www.doh.wa.gov/ehp/ts/WW/TechIssueReports/T-7A-LotSize-SCH.pdf

World Health Organization. 1998. The impacts of cemeteries on the environment and public health. World Health Regional Office for Europe, Copenhagen, Denmark.

Young, T.M. and R.D. Golding. 2002. Underground storage tank system field-based research project report. California State Water Resources Control Board, Sacramento, CA.